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A FEASIBILITY STUDY FOR D-REGION EQUATORIAL IONOSPHERE RESEARCH USING VLF RADIOWAVES

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13. ABSTRACT *(Maximum 200 words)*

(U) This research report establishes experiment feasibility and presents a plan to explore dynamic properties of the equatorial D-region ionosphere. The objective is to derive geophysical information on the lower ionosphere at nighttime in near equatorial regions through the use of a new VLF radiowave measurement method which uses ionosphere mode conversion. The measurement technique uses VLF signals, that when propagating at a range of azimuthal angles (typically 190° to 360°) through the equatorial region (about ±20° magnetic latitude), undergo marked mode conversion. The mode conversion, as predicted by theory and shown by measurement, is so strong that many modes become near equal in amplitude, even modes that when entering the equatorial zone are more than 30 dB below the dominant mode. Signals are strongly mode 1 on entering the mode conversion zone, thus converted modal components provide information on ionosphere parameters causing the mode conversion process. This process is shown to be highly sensitive to ionosphere parameters. Spaced receivers located just within the mode conversion zone will provide data from a small reflection region, even though the transmitter is far away. Theoretical models of VLF propagation, used in an iterative inversion process, infer the parameters of the ionosphere. Topics covered include; measurement concept, mode conversion theory and measurement, literature review, geophysics phenomena to explore, research goals, technical approach and experiment plan.

14. SUBJECT TERMS
D-region, Electron Density, Equatorial Zone, Ionosphere Dynamics, Ionosphere Profiles, Instrumentation, Mode Conversion, Omega Signals, Research, Very Low Frequency, VLF Propagation

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TABLE OF CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

This report describes a feasibility analysis for a planned research project to explore dynamic properties of the equatorial D-region nighttime ionosphere. A major motivation for the planned research is that the lowest D-region, lying in between the upper atmosphere (measurable by balloons) and the lowest ionosphere (measurable by rocket probes) has undergone little investigation. This part of the D-region is suspected to be a transition as well as a transport zone for many important phenomena. Any knowledge gleaned would help fill in the blanks needed to produce a consistent atmospheric model extending from the earth's surface to the top of the ionosphere. The information available from the literature indicates that the equatorial ionosphere is significantly different from the mid or high latitudes. Phenomena unique to the equatorial ionosphere include: converging winds, ionosphere troughs parallel to the equator, large and widespread ionosphere current systems, high scintillation, formation of large chimneys of depleted ionization, and anomalous Very Low Frequency (VLF) radiowave propagation. Our review of the limited VLF phase data available shows that dynamic effects occasionally occur on trans-equatorial propagation paths that appear to have much different characteristics from those we have observed from propagation on mid-latitude paths.

The meteorology of this region is also unique, this region being the boundary for the two great hemispherical weather systems. In this region much of the low altitude material is carried upwards and then transported to high latitudes. Since major climate modifications are occurring at equatorial latitudes, i.e. deforestation, it is suspected that a better understanding of the relation of the equatorial region to the rest of the world would be most beneficial. This region is also the heat source for much of the planet. We thus suspect that the equatorial zone D-region sandwiched between the major atmospheric and ionospheric regimes, and likely experiencing coupling from both, also has unique characteristics relative to the rest of the planet.

While the research objective is to acquire new knowledge of nighttime equatorial D-region ionosphere dynamic properties, a new measurement technique will be developed and used. In fact, it is the new measurement technique that makes the research feasible. The planned technique, described in more detail later,

makes use of the fact that VLF signals, when propagating at a range of azimuthal angles (typically 190 to 350 degrees) through the equatorial region (about ±20 degrees magnetic latitude), are predicted by theory to undergo very marked mode conversion. The predicted mode conversion is so strong that many modes become nearly equal in amplitude, even modes that when entering the equatorial zone are more than 30 dB below the dominant mode. The mode conversion process is expected to be highly sensitive to ionosphere parameters. The signal at a group of receivers, placed to sense the modal content, is the composite of many modes and has an amplitude and phase that is dependent on ionosphere parameters and the distance from the reflecting position. Since the signal consists of one strongly dominant mode on entering the mode conversion zone, the modal components of the signal provide information on the mode conversion process. If a receiver is located so that just one reflection occurs within the mode conversion zone, the modal content will be primarily from this single reflection region. Since propagation of each of the modes has a different attenuation rate and phase velocity, the composite signal will vary with distance from the reflecting region. Thus the data from several properly spaced receivers will reveal a signal amplitude and phase structure that characterizes the wave interaction with the ionosphere. Theoretical models can be used in an inversion process to infer the parameters of the ionosphere. The technique is expected to be relatively inexpensive and easy to implement. Interpretation of the data in terms of ionosphere parameters will, however, require a significant learning curve.

This small feasibility study, approximately one third man-year of effort, enables us to develop the experimental concept sufficiently to justify its development and implementation. In this report we will (1) provide some background leading to proposing the experiment, (2) present the analysis material showing the theoretical basis for the technique, (3) describe data supporting the existence of mode conversion, (4) describe the overall project as presently visualized, including the required preparation, and (5) present the planned effort. As will be described, the project is proposed in well-defined phases, with the conduct of each phase predicated on the success of the previous phase and each phase having a well-defined research product.

2.0 BACKGROUND

In this section we will summarize our perspectives at the start of this feasibility study regarding the use of VLF radiowave signals to study the dynamic properties of the nighttime equatorial ionosphere.

VLF radio propagation theory shows that the equatorial ionosphere can produce anomalous propagation, at nighttime and over a range of propagation radials, in which very high rates of mode conversion occur. Modes –40 dB in relative amplitude rapidly grow to compete with the dominant mode. Five to six modes may become nearly equal over the interacting region. Following this strong interaction most of the modes quickly die out again, but the resulting dominant mode may be significantly altered from the wave that enters the interacting region. Our preliminary analysis and data interpretation gave much credence to being able to exploit this mode conversion as a tool to investigate the dynamics of the ionosphere D-region.

The VLF interaction phenomena pose both a practical problem and a research opportunity. The problem is that modal interaction, which is poorly understood, can significantly modify a signal, especially its phase consistency as it traverses the interacting region. As an example, the occurrence of mode switching can make an Omega navigation signal useless over large regions, 90° in latitude and longitude. (The resulting dominant mode is not included in the navigation model nor is prediction of which mode to select.) Furthermore, in some regions several transmissions are rendered useless at the same time. Experimental evidence we examined shows that such situations do occur, but that the conditions produced are highly variable. Very little is known about how frequent or variable modal conditions are. The message is that the theoretical models used to predict propagation need much better inputs regarding ionosphere parameters and their variability. Historically, VLF radiowave modal effects have been investigated from the perspective of the problems imposed for system applications. Since we could not find a good review discussion of VLF propagation modal effects, we have chosen to provide an overview. Our objective is to place our planned use of modal conversion effects in perspective.

2.1 VLF MODAL EFFECTS

The VLF radiowave propagates within the earth and ionosphere boundaries as a guided wave. The physical dimensions of the waveguide allow more than one mode to be excited and to propagate within the waveguide. Within the VLF navigation (9 to 14 kHz) and communications (15 to 30 kHz) bands the guide height in wavelengths changes considerably. The guide height (radiowave reflection height) is typically 65 to 70 Km during daytime and 84 to 90 Km during the night. The sunrise and sunset transitions produce a change in guide height that varies with distance. Since the wavelength dimensions of the waveguide change greatly with frequency and from day to night, the modal effects also vary greatly across the VLF band. This is illustrated in Figures 1 (a), (b), and (c) and 2 (a), (b), and (c), which show respectively the measured amplitude and phase obtained with a multi-frequency VLF sounder on a propagation path from Hawaii (19.642°N, 155.60°W) to southern California (34.533°N, 116.625°W) obtained by Hildebrand [Ref. 1]. This path was 4.166 megameters in length; its mid-path point (28.48°N, 137.47°W) has a magnetic field strength of 0.425 gauss and a magnetic dip angle of 50°. The mid-path magnetic field angle with respect to the path of propagation (magnetic azimuth) is 50.6°. Several different modal phenomena are evidenced in this data which will be described as follows.

Modal effects can be placed in two categories: those resulting (1) from mode excitation at the transmitter, and (2) from excitation along the propagation path. The modal effects of both categories are dependent upon geophysical parameters, namely the ionosphere electron density profile and the earth's magnetic field. The ionosphere profile varies in shape and height, resulting in differing radiowave penetrations into the ionosphere and in differing reflection heights. The magnetic field dependence is related to the orientation of the reflecting radiowave to the magnetic field. The orientation results in a directional and latitude dependence of the radiowave reflection properties. In the equatorial zone a range of orientations results in modal excitation. The various dependencies will be illustrated with a series of calculations produced by Gupta [Ref. 2] using the parameters shown in Table 1. This calculation data was made available to us by the U. S. Coast Guard Omega Navigation Systems Center (ONSCEN).

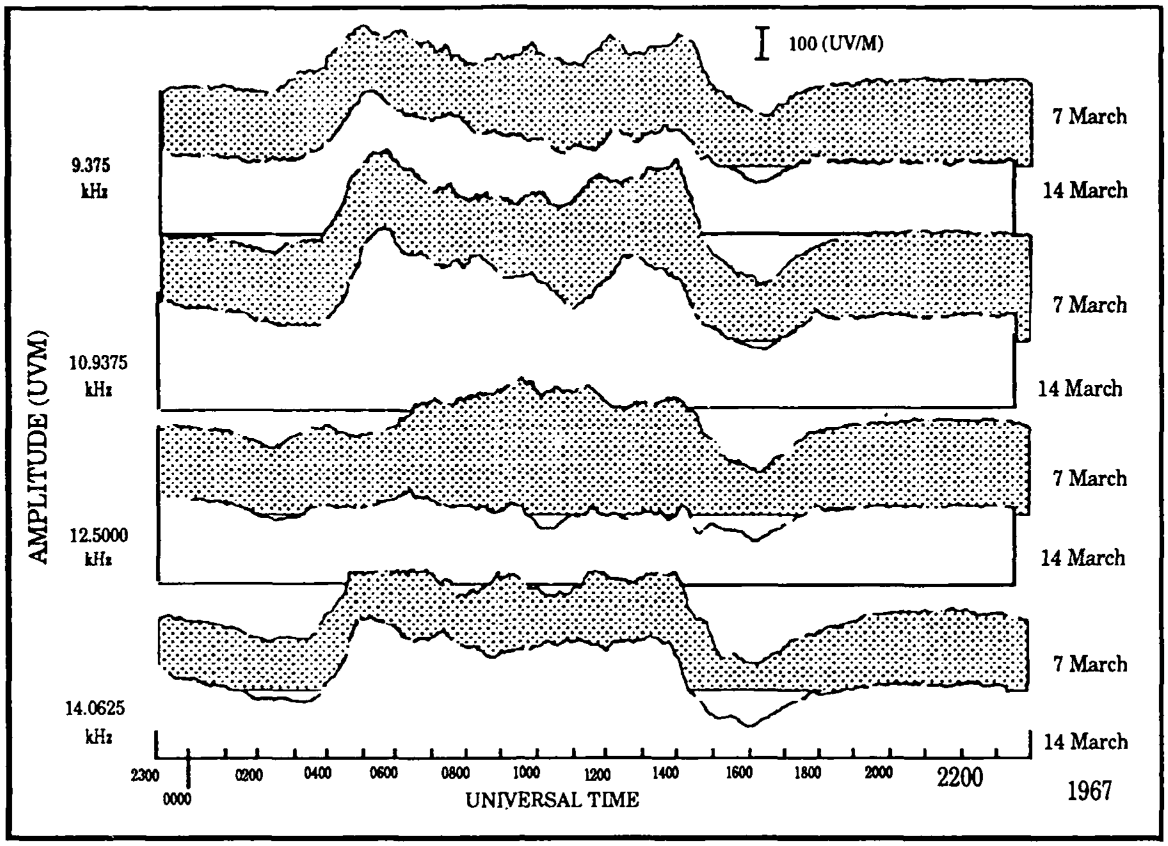

Figure 1(a). Amplitude of Recieved Signals (9.3 to 14.06 kHz)

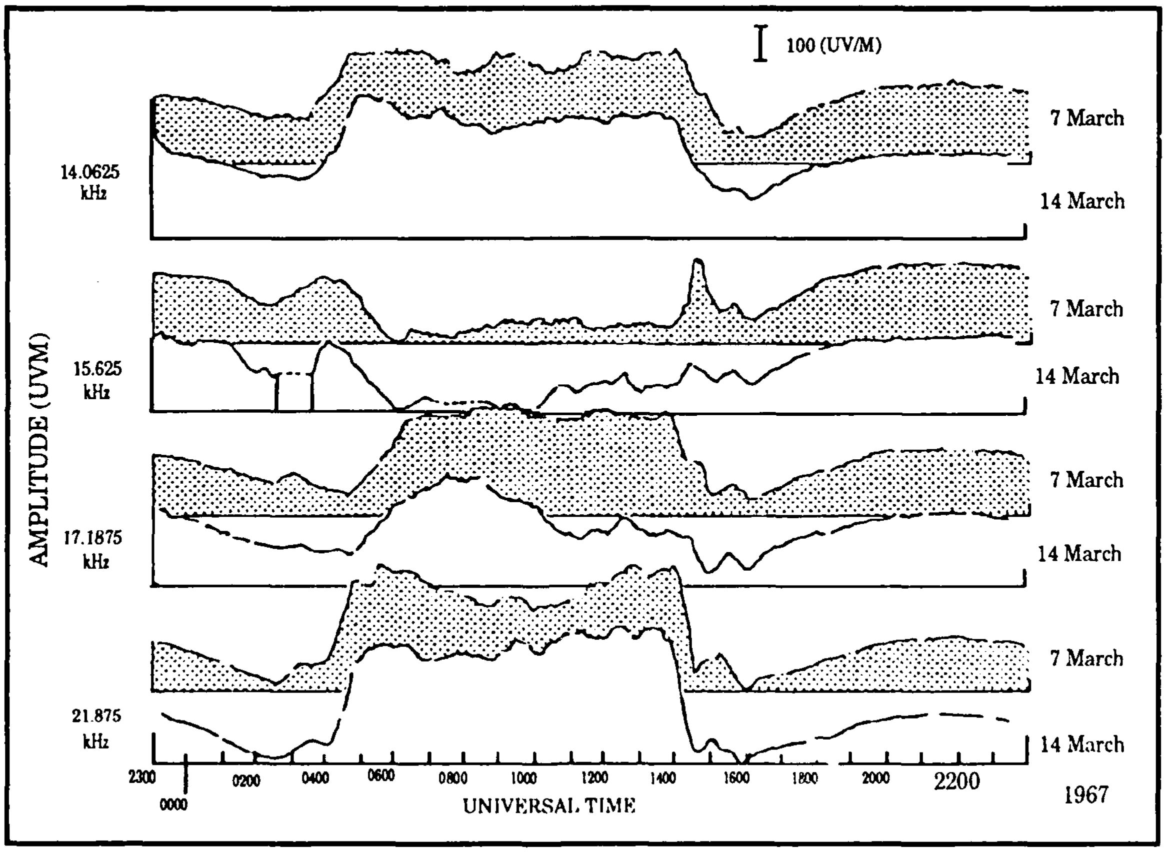

Figure 1(b). Amplitude of Recieved Signals (14.06 to 21.8 kHz)

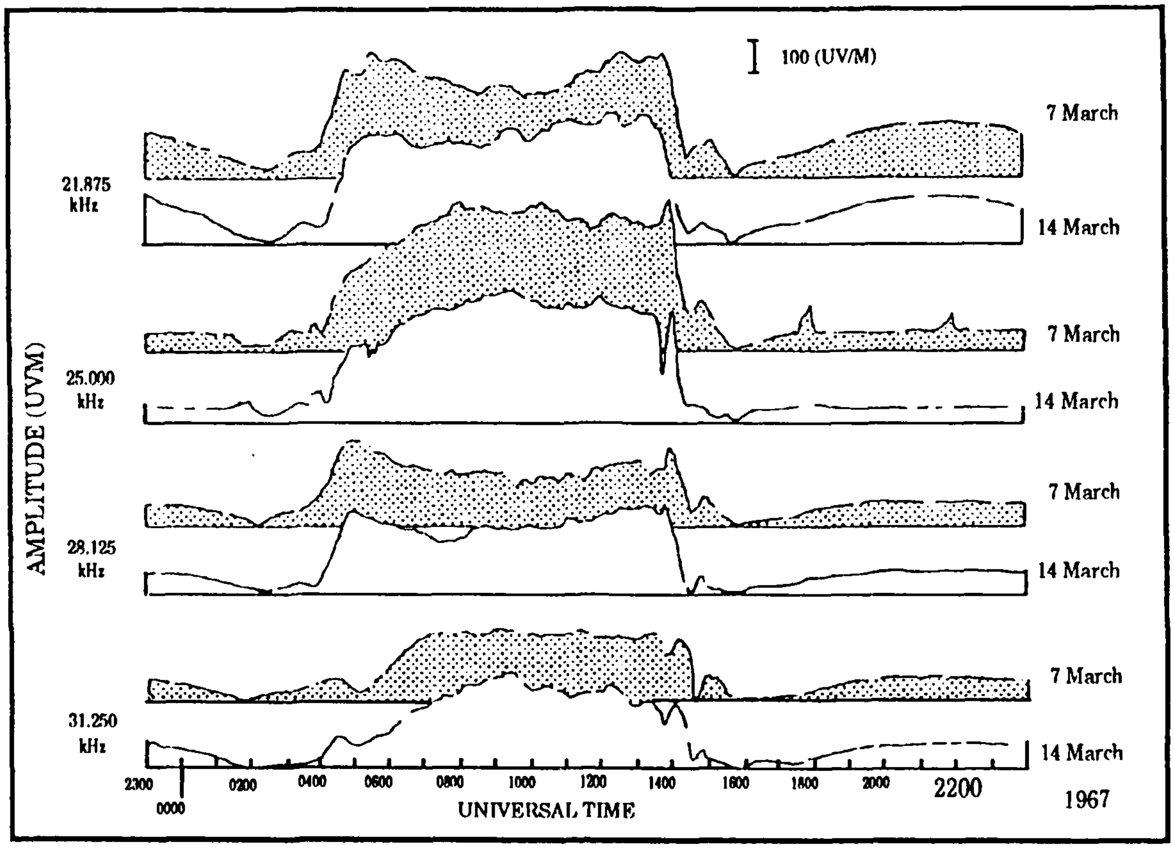

Figure 1(c). Amplitude of Recieved Signals (21.8 to 31.2 kHz)

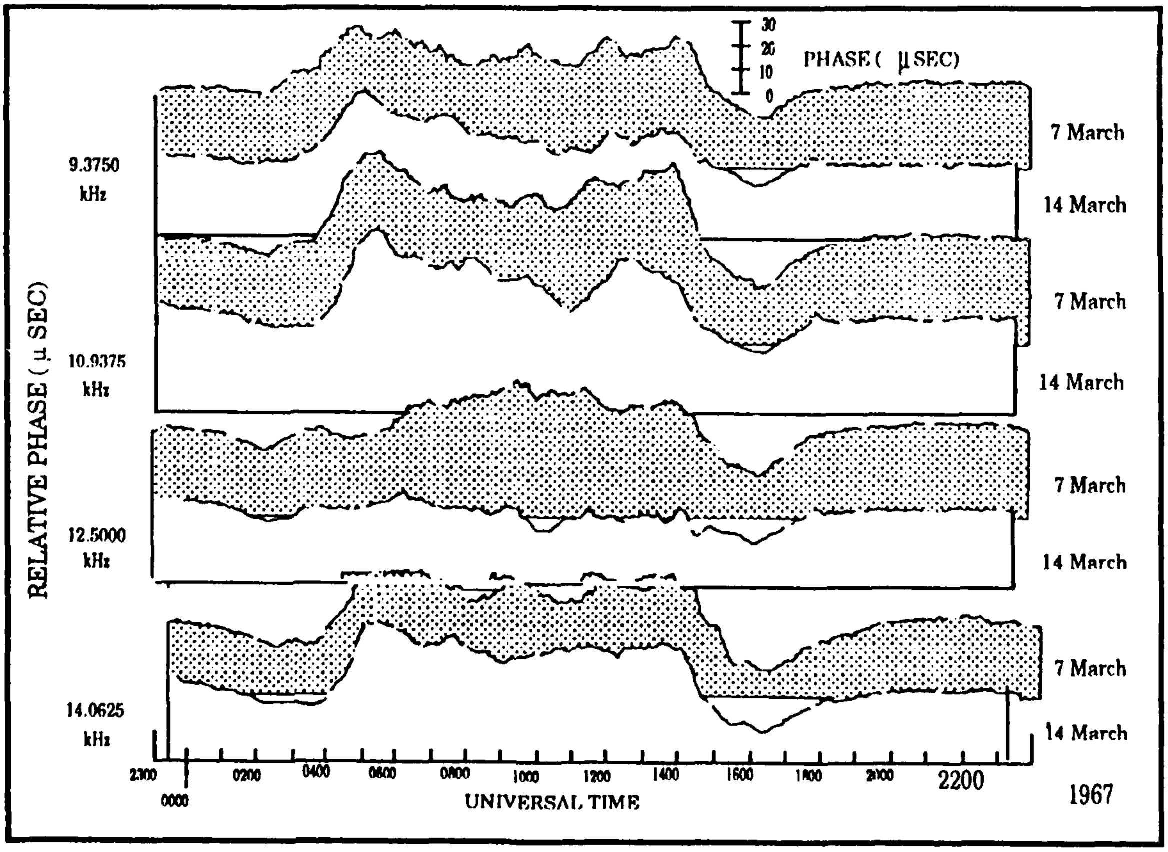

Figure 2(a). Phase of Recieved Signals (9.3 to 14.06 kHz)

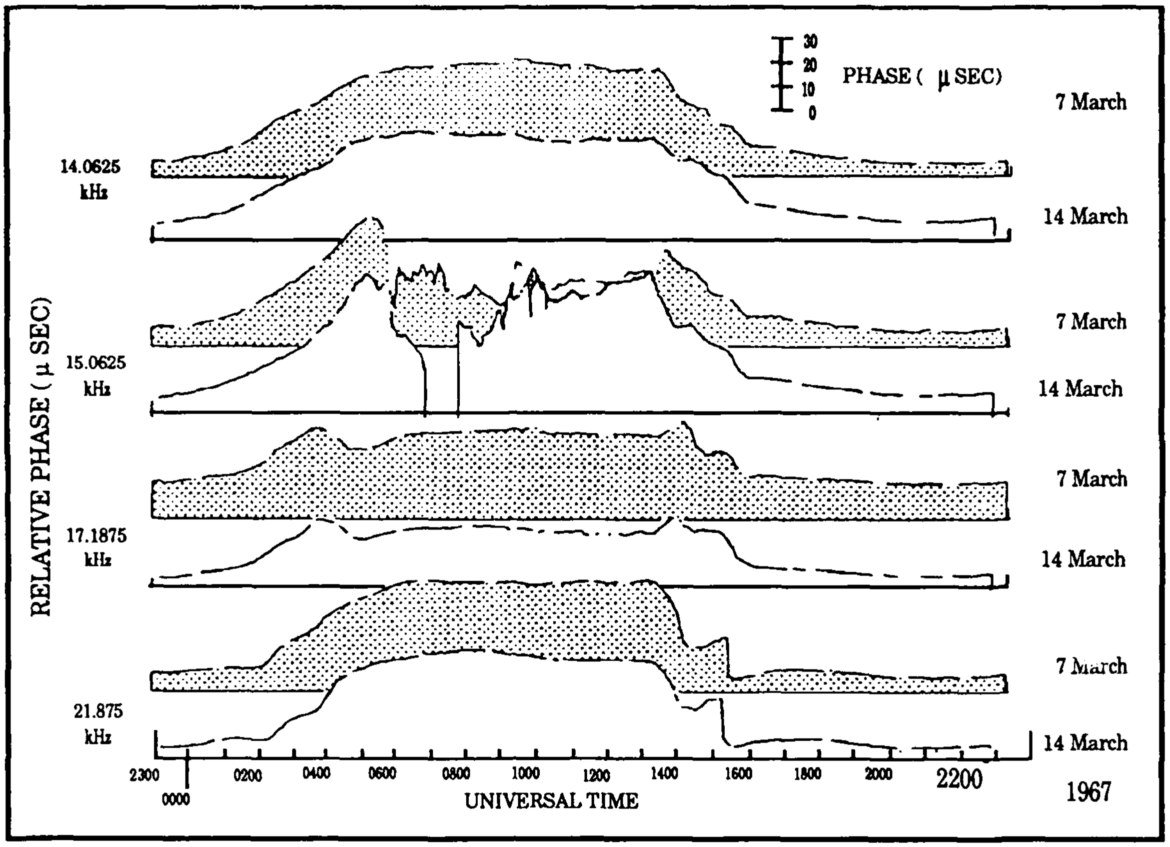

Figure 2(b). Phase of Received Signals (14.06 to 21.8 kHz)

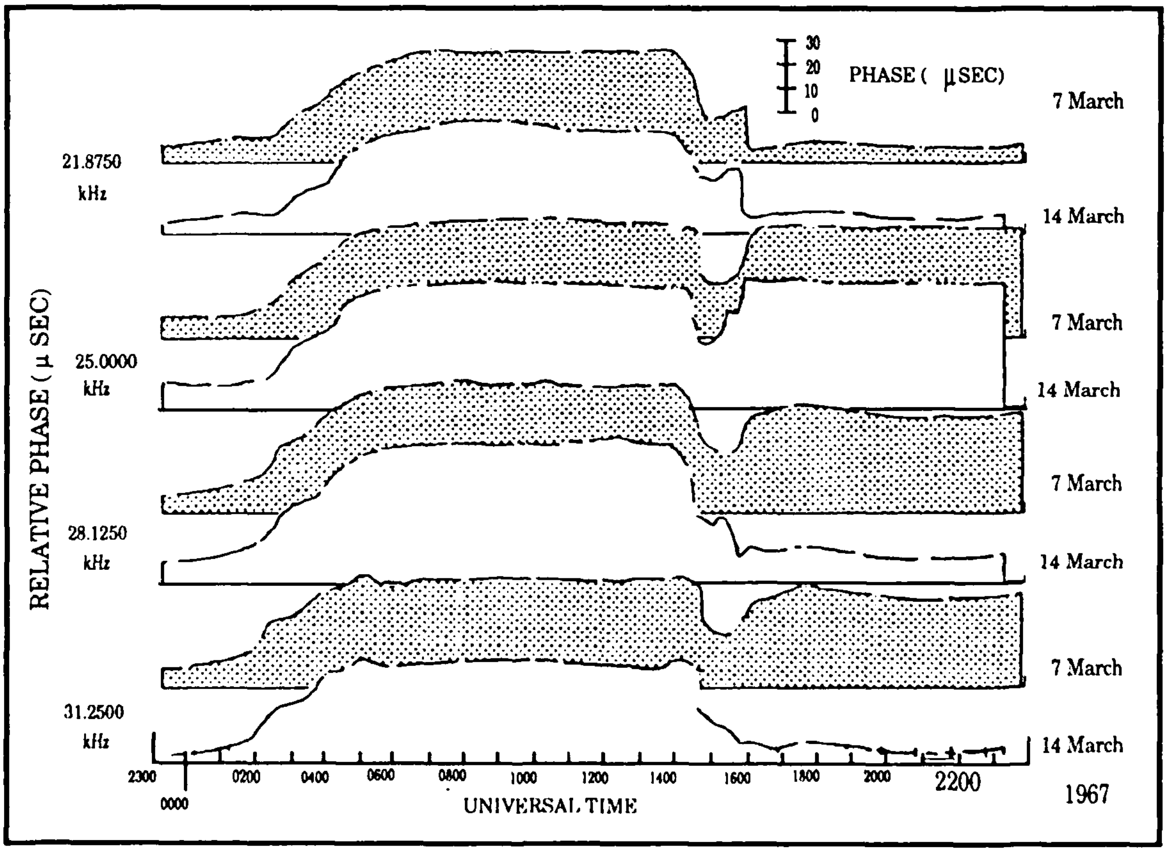

Figure 2 (c). Phase of Received Signals (21.8 to 31.2 kHz)

Ionosphere Illumination Condition	IONOSHERE PARAMETERS	
	Reflection Height (Km)	Conductivity Gradient (Km) $^{-1}$
Day	70	0.3
Night	87	0.5

Table 1. Day and Night Ionosphere Parameters

2.1.1 PROPAGATION OF MODES EXCITED AT THE TRANSMITTER

The day/night and frequency dependency is illustrated by comparing Figures 3 and 4, which show calculations of field strength versus distance for the 10.2 and 13.6 kHz Omega navigation frequencies, and for day and night. The calculations are representative of the predicted propagation conditions on the path from the island of Hawaii to southern California, Figures 1 and 2. We note from Figures 3 and 4 that two modes, modes 1 and 3, are about equal magnitude at the transmitter. For daytime propagation, Figure 3, mode 3 has a very high attenuation rate and soon has no influence on the total field. For nighttime propagation, Figure 4, the mode 3 attenuation rate is less, and the influence extends to much greater distances. This third mode propagates at a lower phase velocity than the first mode, so that the relative phase changes with distance. This changing phase relationship causes the amplitude of the composite field to fluctuate with distance as the modes add alternately, constructively and destructively. The distance interval for the calculation values in this series is too large to optimally show the cyclic detail. A smaller distance interval would show the amplitude variation to be sinusoidal. The dB plots will result in broad maxima and narrow minima, for deep fades. Many of the minima are lost by the calculation resolution. The second minima of Figure 4(a) is a case in point. More detailed calculations would likely show this minima to extend to about 52 dB. Note that the composite signal amplitude fluctuation, indicating modal effects, is larger and extends farther at 13.6 kHz than at 10.2 kHz. For the nighttime case, Figure 4(b), the third mode initially is stronger than the first mode. Note also that the

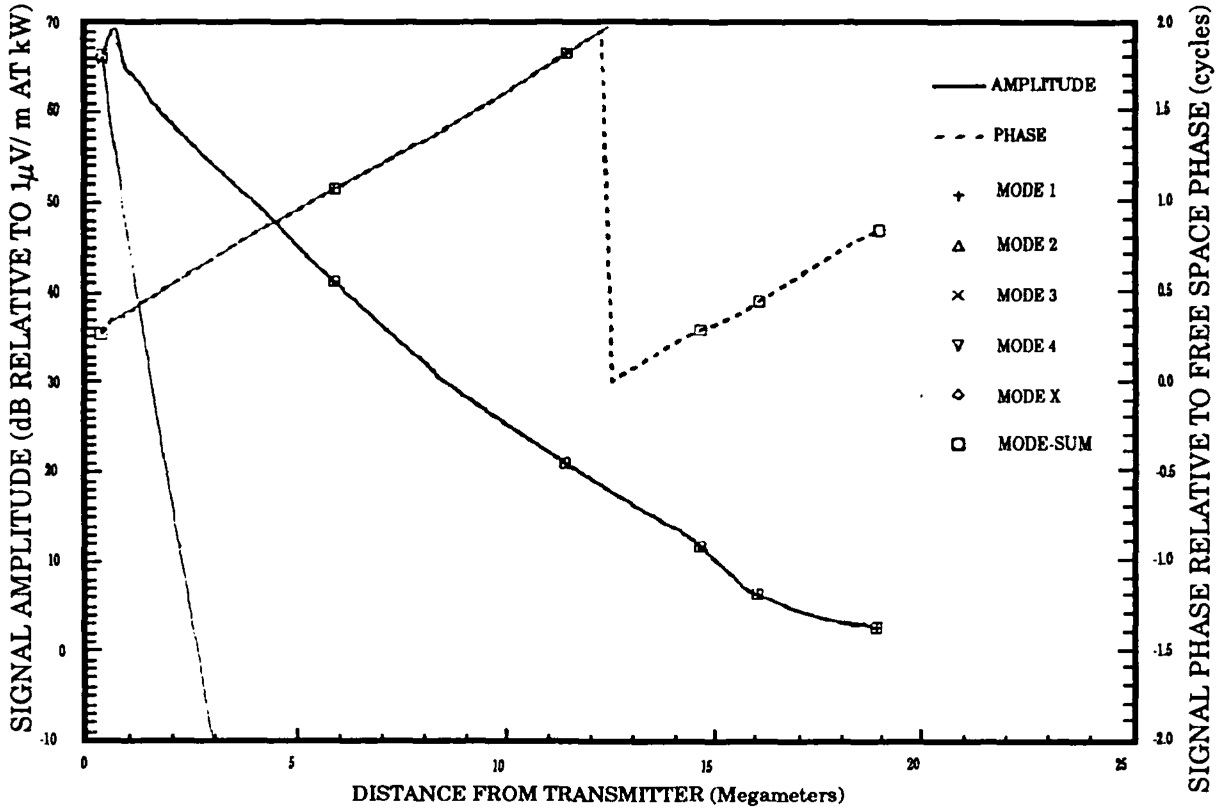

Figure 3(a). Hawaii 10.2 kHz Signal: Day, 50 Degree Radial

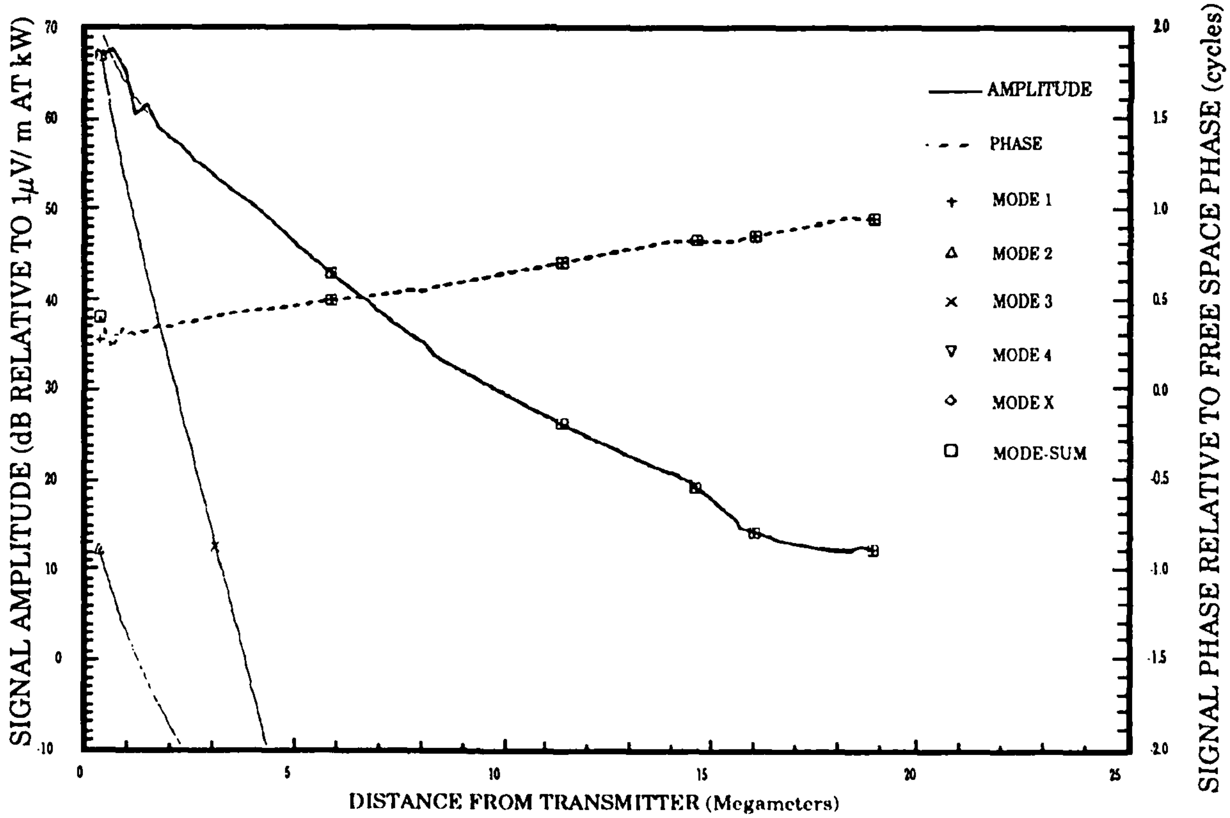

Figure 3(b). Hawaii 13.6 kHz Signal: Day, 50 Degree Radial

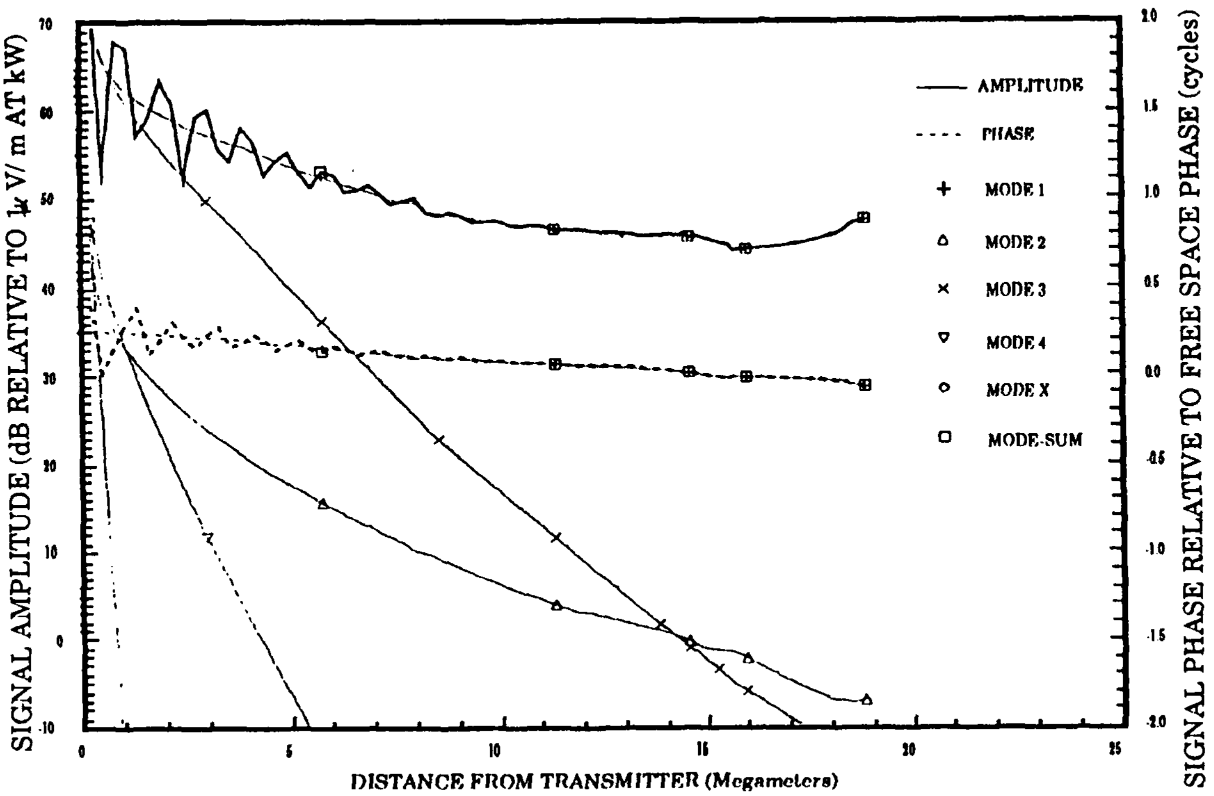

Figure 4(a). Hawaii 10.2 kHz Signal: Night, 50 Degree Radial

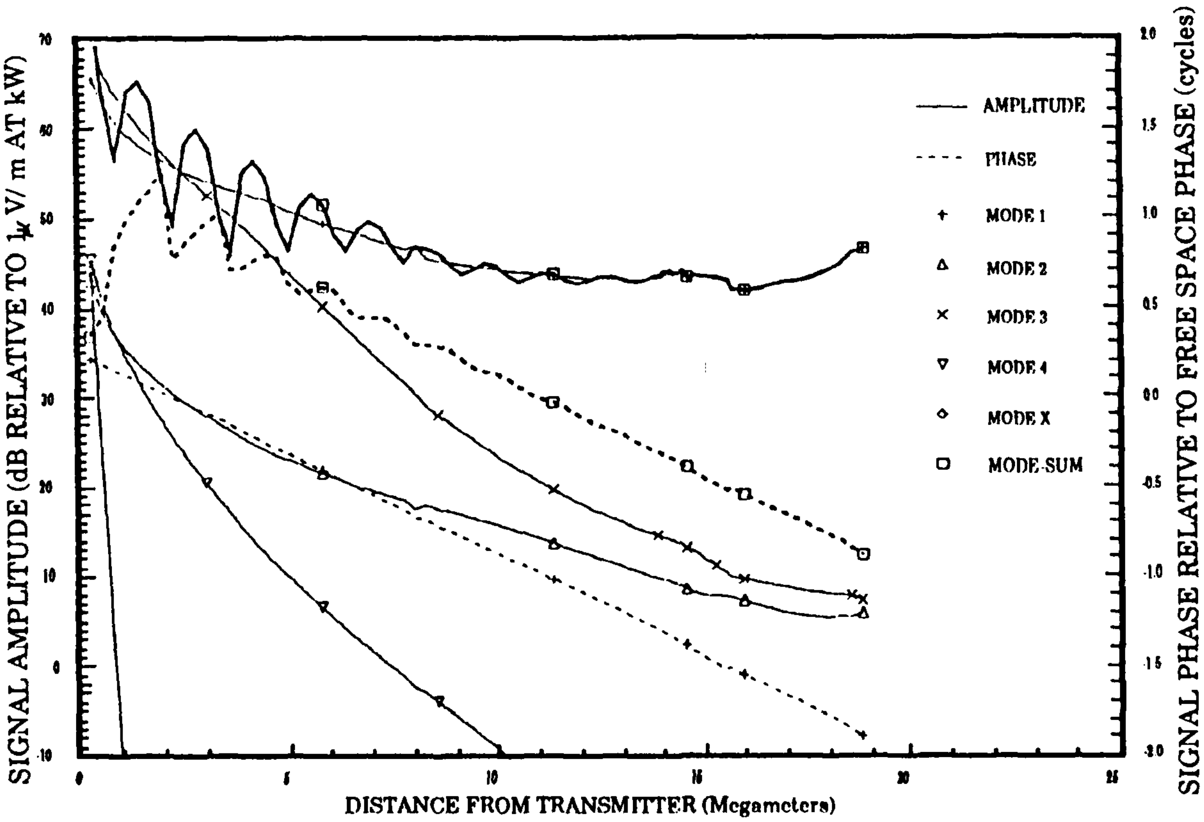

Figure 4(b). Hawaii 13.6 kHz Signal: Night, 50 Degree Radial

composite phase, indicated by the heavy dashed line, shows fluctuations due to the presence of two or more modes. In Figures 3 and 4 the second mode and modes higher than three are poorly excited and have very high attenuation rates.

The data of Figures 1 and 2 confirms these calculations with many features.

First, the daytime signal at the lower frequencies is single mode. The daytime single mode is evidenced by a consistent amplitude and phase pattern that shows the amplitude to be maximum and the phase to be minimum at midpath noon (approximately 2130 UT). At this time, the solar ionization production is maximum and the ionosphere produces the lowest and most efficient reflection.

Second, minor daytime modal interference effects are detected as frequency increases. The first evidence appears at 21.8 kHz in the phase data, particularly for the 14 March date. While the amplitude data shows an increasingly pronounced solar zenith angle effect with increasing frequency through 21.875 kHz, the phase data shows a minor oscillation with the mid-morning change being opposite of that expected from a lowering reflection height. Above 21.875 kHz the amplitude data also shows slight evidence of daytime modal effects. The multi-mode content during the day is not large for any of the frequencies shown.

Third, the evidence for nighttime modal interference effects, while slight, can be detected at the lowest frequencies by comparison of the 9.3750 and 10.9375 kHz frequencies. For example, following sunset the 10.9375 kHz signal takes over an hour longer to reach its nighttime value. The 9.3750 kHz frequency phase record is a nearly classic example of a single mode diurnal record, indicating that any higher-ordered mode content is at best minimal. At 12.5000 kHz the diurnal phase change is notably reduced, and the amplitude record has a nighttime pattern quite different from the 10.9375 kHz frequency. The marked amplitude increase in late sunset at 10.9375 kHz is missing at 12.5000 kHz. The amplitude depression during the middle of the night at 10.9375 kHz is inverted into a hump at 12.5000 kHz. The higher-ordered mode content is clearly getting larger with increasing frequency.

Fourth, the nighttime modal effects become very significant with increasing frequency. By 15.6250 kHz the nighttime phase undergoes a sharp reversal after sunset followed by a gradual drift to near normal at sunrise that is accompanied by a marked amplitude decrease. This pattern of alternately constructive and destructive modal contributions progresses becoming more pronounced as frequency increases.

Other features of this sounder data, namely sunrise and sunset mode conversion, can be used to describe modal effects occurring on VLF propagation. First, we will continue with our discussion of modal effects resulting from modes excited at the transmitter. The mode excitation efficiency and attenuation rates vary with the ionization profile and wave orientation relative to the earth's magnetic field. The magnetic azimuth effect can be illustrated by comparing Figures 4 and 5. Note how in going from a 50° to a 110° radial, the modal structure extends in distance and changes in pattern. This results from two factors, mode 3 at the 110° radial is more strongly excited, and the attenuation rate is much reduced. At 13.6 kHz, mode 3 is dominant out to 9.5 Mm. Note that at 13.6 kHz the phase slope is rapidly increasing until mode 1 dominates, after which it is negative.

Under other magnetic field conditions the modal excitation and attenuation rates can be quite different. To illustrate, Figure 6 shows nighttime propagation calculations for the Argentina Omega transmitter along a 230° radial. For this case mode 3 is the most strongly excited, but its attenuation rate is so high that it has very little influence on the composite signal beyond 1 Mm at 10.2 kHz and 2 Mm at 13.6 kHz. However mode 2, which is more weakly excited than either mode 1 and 3, and initially has a greater attenuation rate than mode 1, soon incurs a lower attenuation rate and eventually becomes the dominant mode. In fact, the 10.2 kHz calculation shows a negative attenuation rate beyond 9 Mm. We have not studied this condition, but from the curves one could infer that mode conversion from mode 1 to mode 2 is occurring. Our rationale is that the attenuation rate of mode 1 appears to be increasing as the attenuation rate for mode 2 lessens. The calculation results for distances beyond 13 Mm will be described later.

Turning to the calculated fields shown in Figure 7 for a 190° radial from Hawaii, we note that the nighttime modal structure extends only for a very short dis-

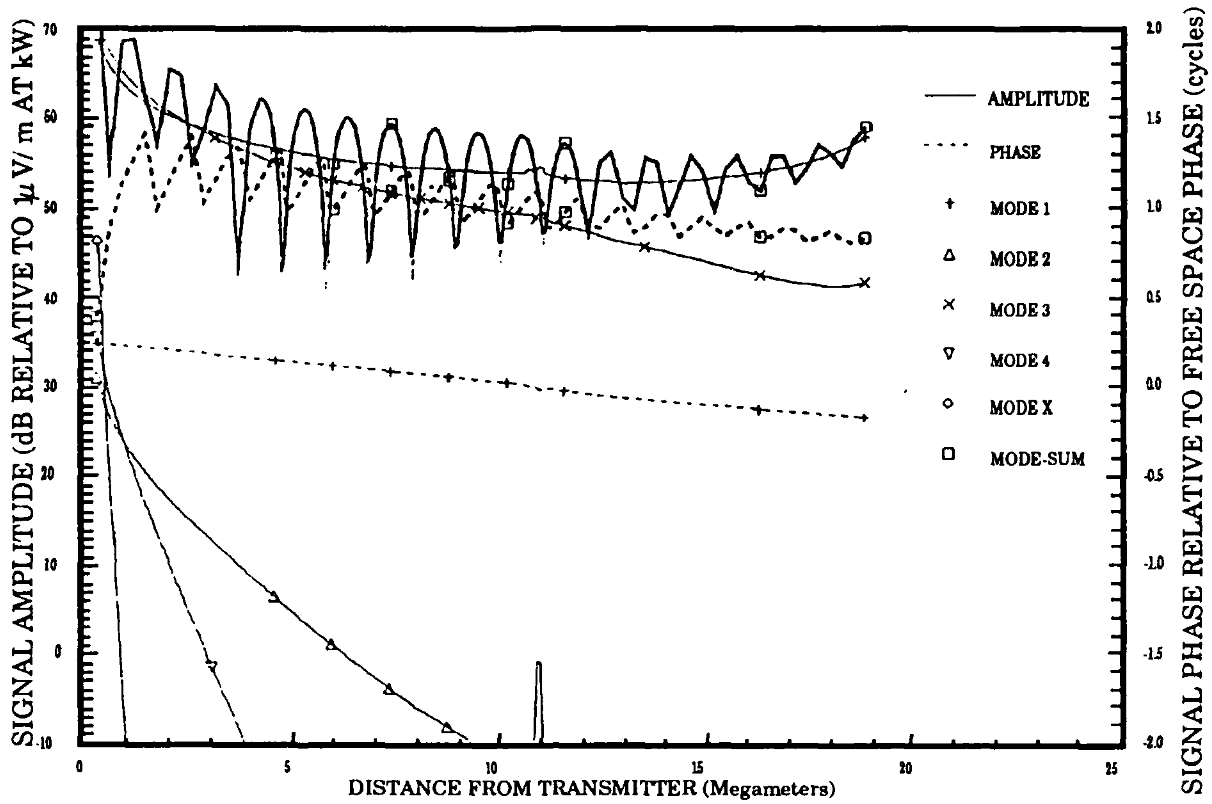

Figure 5(a). Hawaii 10.2 kHz Signal: Night, 110 Degree Radial

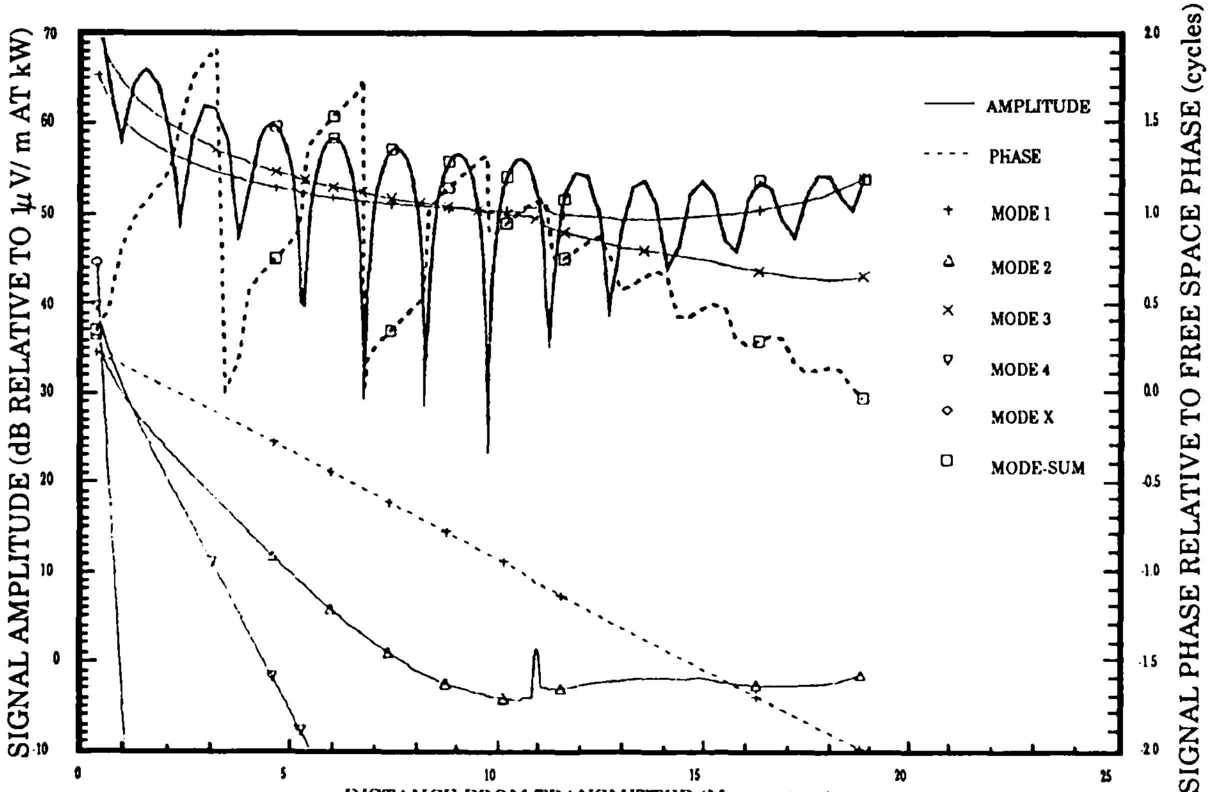

Figure 5(b). Hawaii 13.6 kHz Signal: Night, 110 Degree Radial

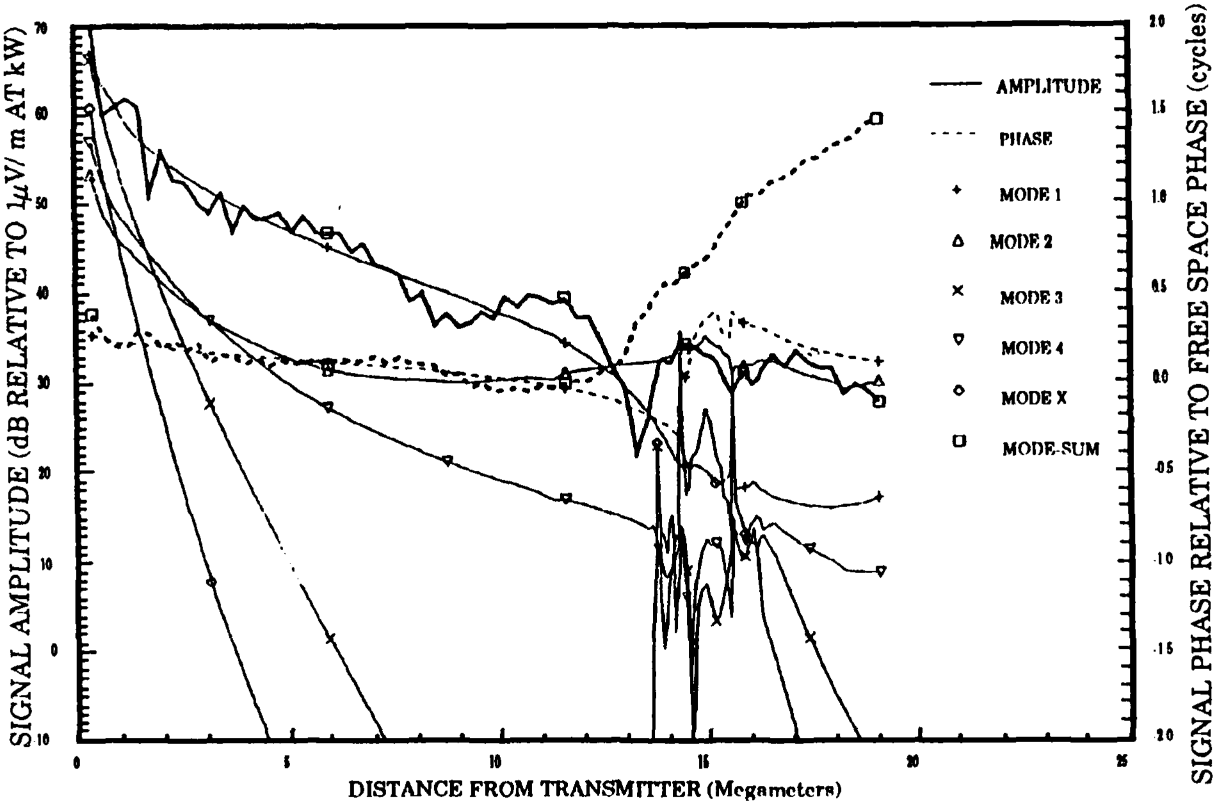

Figure 6(a). Argentina 10.2 kHz Signal: Night, 230 Degree Radial

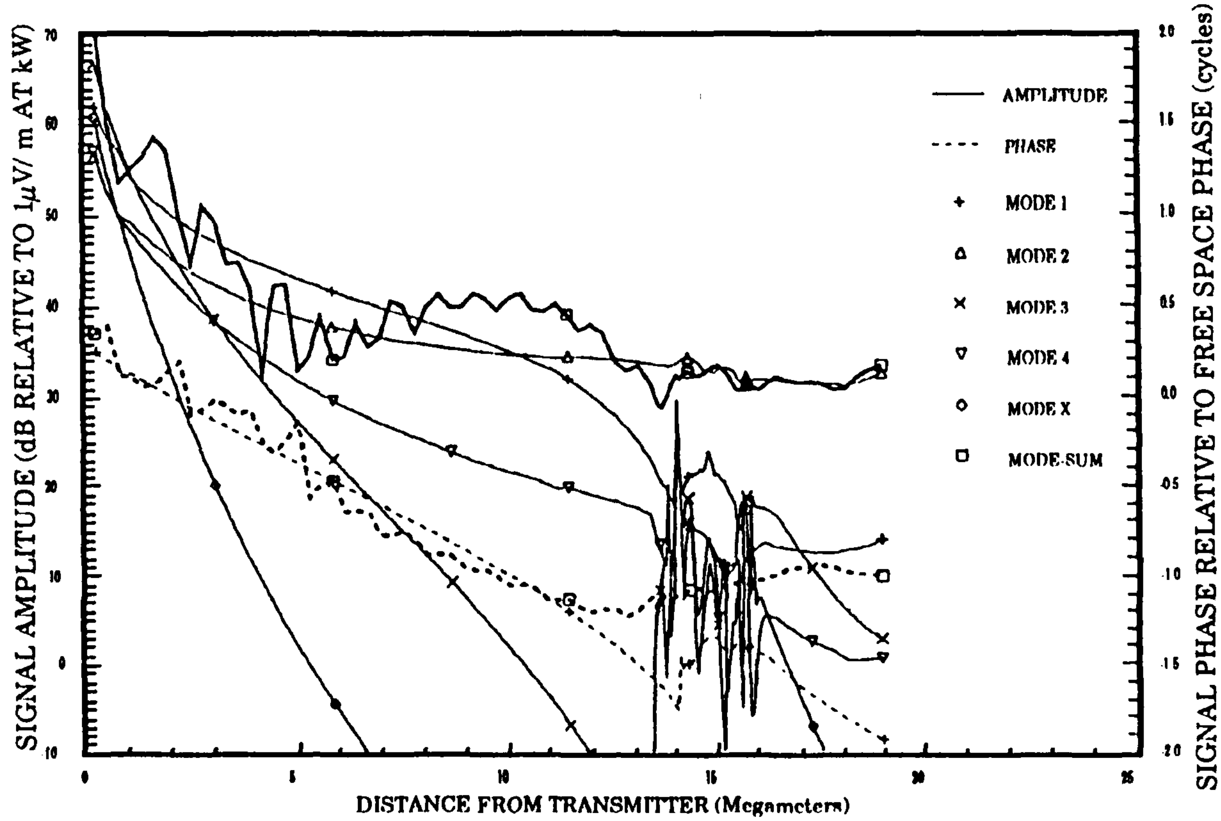

Figure 6(b). Argentina 13.6 kHz Signal: Night, 230 Degree Radial

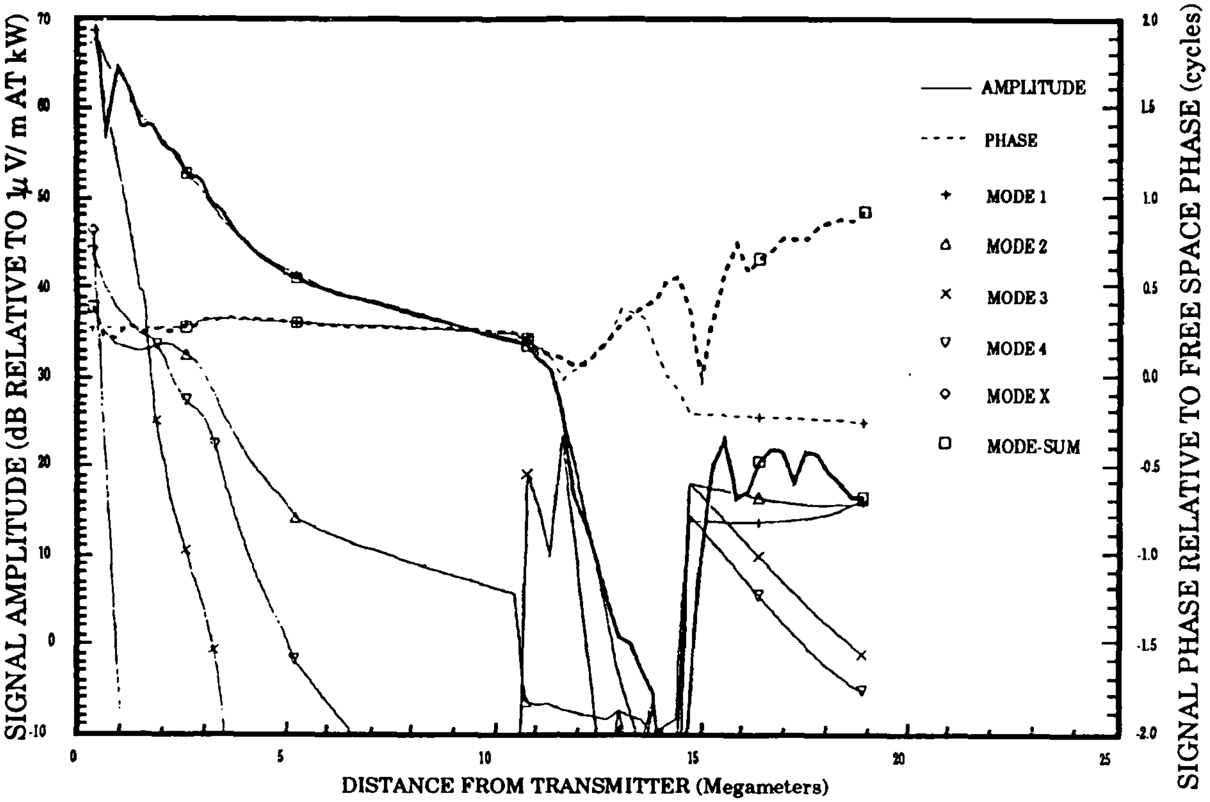

Figure 7(a). Hawaii 10.2 kHz Signal: Night, 190 Degree Radial

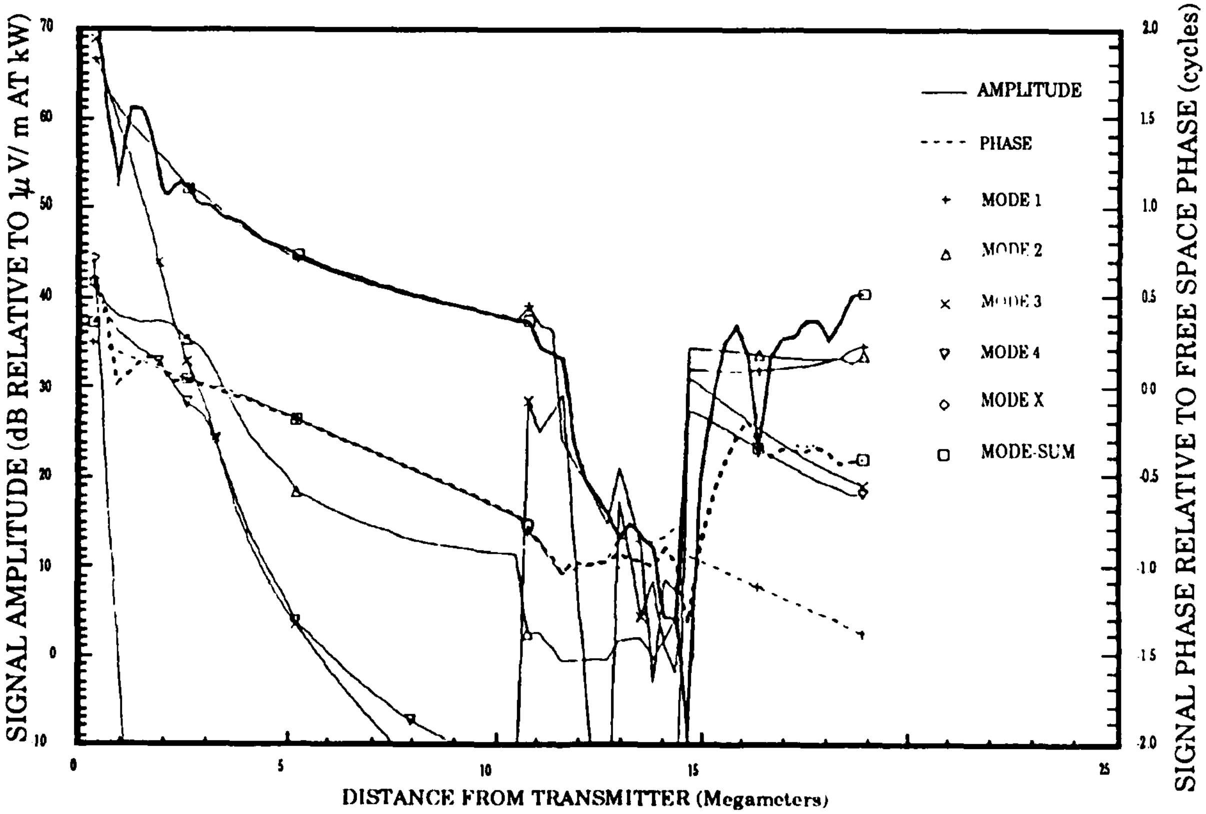

Figure 7(b). Hawaii 13.6 kHz Signal: Night, 190 Degree Radial

tance. Mode 3 has a very high attenuation rate. Mode 2 is weakly excited, –25 dB relative to mode 1, and has a higher attenuation rate than mode 1. The field structure beyond 10 Mm results from propagating across Antarctica. We emphasize that the very pronounced modal structure shown in Figure 5 is no longer present. The differences between calculated nighttime fields for this series of radials from Hawaii is entirely due to orientation relative to the earth's magnetic field. We note that all calculations were made using the ionosphere parameters shown in Table 1.

As stated above, the mode attenuation rate for any given propagation path is influenced by the profile shape and height. At this time we do not have calculation examples to illustrate this effect. As will be described later in the report, we are in the process of establishing our computational facility and are not able to produce the desired calculations. Later we will illustrate with measurement data that propagation parameters, and thus the ionosphere, have to be changing greatly over time.

To summarize, the effects from modes excited at the transmitter are related in a complex manor to magnetic field and profile parameters on the propagation path. As we will describe later in this report, interpretation of propagation data is greatly facilitated by a good understanding of modal interaction. When multiple modes are contributing to the composite signal, multi-frequency data is vital to interpretation of the propagation conditions.

2.1.2 MODES EXCITED BY CONVERSION ALONG THE PROPAGATION PATH

Three important mechanisms produce mode conversion in VLF propagation. These are conversion due to (1) waveguide height changes, (2) large changes in ground conductivity, and (3) certain magnetic field orientations at ionosphere reflection.

Day/Night Terminator Mode Conversion: The mode conversion resulting during sunrise and sunset transitions on the VLF propagation path was studied first, (see for instance, [CROMBIE, Ref. 3 and 4], [WAIT, Ref. 5], [BAHAR, Ref. 6], [LYNN, Ref. 7] and [PAPPERT, Ref. 8]). Crombie published the first satisfactory

model in 1964 [CROMBIE, Ref. 3]. This model for sunrise and sunset transitions, has two parts as shown in Figure 8. In case (a), a single waveguide mode propagating from the daylight portion into the reflection discontinuity between day and night results in the generation of several modes that propagate away from the far side of the discontinuity. Or in case (b), two modes propagating in the night portion of the path when incident on the reflection discontinuity will result in a single mode propagating into the daylight portion that contains energy converted from the higher-ordered mode. The interference between the modal components produces regular phase and amplitude perturbations at the receiver during the transitions. These effects are best observed when the daytime propagation path is single mode. The fades associated with sunrise are more pronounced than those associated with sunset, indicating that the sunrise transition produces a greater waveguide discontinuity than the sunset. The distance travelled by the sunrise line along the path between successive signal fades (the phase opposition condition) provides a measure of the relative phase velocity between the propagating modes. The depth of the fade provides a measure of the mode relative amplitudes. Walker [Ref. 9] published the first detailed experimental confirmation of the Crombie theory. A sample of the data published by Walker showing the recorded phase steps and amplitude fades on a path from transmitter NBA, Balboa Canal Zone to Nairobi and to a ship between NBA and Nairobi, is shown in Figure 9. Lynn [Ref. 10] studied the frequency dependence of the distance the terminator traveled between fades during sunrise.

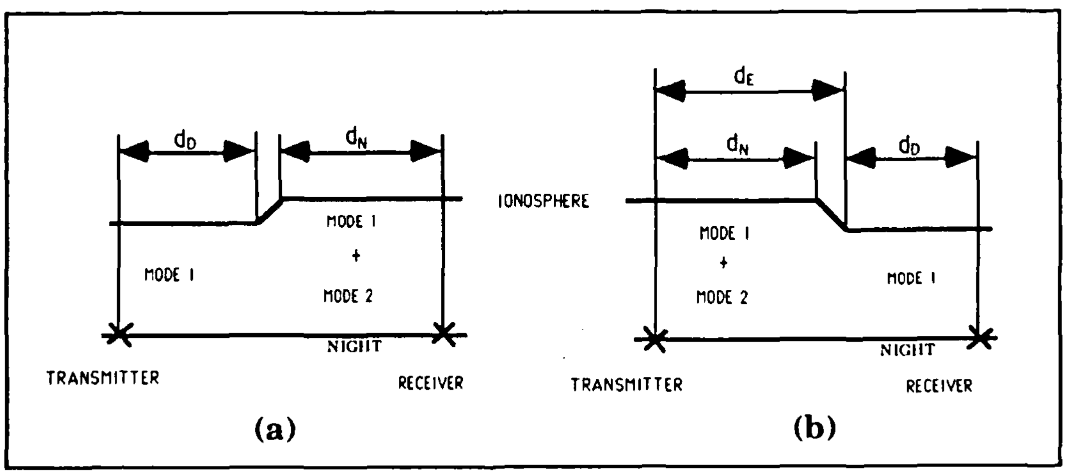

Figure 8. Inosphere Model for Sunrise and Sunset

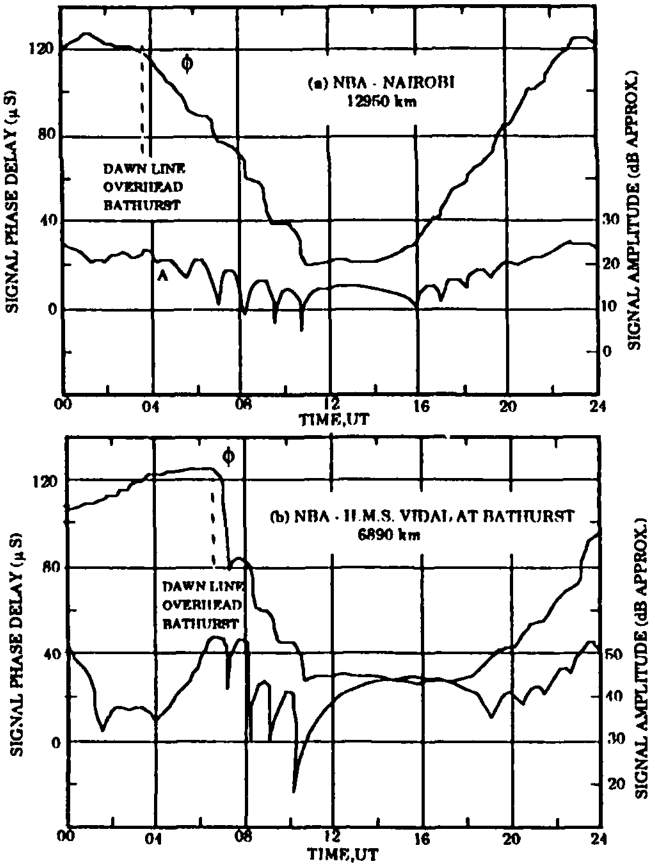

Figure 9. NBA 18.0-kc/s Phase (ϕ) and Amplitude (A) Records, 6 December 1963.

Lynn [Ref. 11] also studied transequatorial paths for which he observed anomalous values for the fade intervals and amplitude ratios. The multi-frequency sounder data of Figures 1 and 2 clearly shows both the sunset and sunrise phase steps and amplitude fades attributed to terminator mode conversion. The frequency dependence of the fade intervals and fade depths could easily be derived from this data, but to our knowledge this has not been done. Collectively this research has shown that much can be learned about nighttime modal propagation by observing the sunrise/sunset modal conversion effects. We would caution, however, that the simplified models of modal effects used in the early years could lead to incorrect interpretations. We note, the calculations show that on some nighttime paths modes 1 and 3 are the principle modes (see Figure 5) and on others, modes 1 and 2 are the most significant (see Figure 6). Also, when mode dominance switching occurs, such as predicted in Figures 5(b) and 6(b), the interpretation of successive fades and steps could be misleading. While the

calculations should not be taken as fact, a full awareness of their products is important. There is great value in iteratively using calculations to guide and interpret experiment and vise versa.

Mode Conversion due to Earth Conductivity Discontinuities: Signal loss due to low conductivity terrain, such as caused by the Greenland and Antarctic ice caps, has been extensively studied. Such large signal loss is incurred during daytime propagation over large regions of low conductivity, that the traversing signals are too weak to be useful. The mode conversion, a nighttime phenomena, is not nearly as well understood. The prevailing viewpoint seems to be that while very high mode conversion occurs over the low conductivity terrain, once the terrain is traversed the modes rapidly attenuate and the mode 1 remains dominant. The calculations we have used for our study show that for many radials, mode 2 is predicted to be dominant following the low conductivity traversal. This is illustrated in Figure 10, which shows the Omega Norway signals propagating across Greenland on a 340° radial. The validity of these calculations has been questioned, and to our knowledge has not been confirmed with measurements. Other calculations for 50° and 70° radials from Norway are of particular interest because these radials pass close to Yap Island, Cubi Point in the Philippines and Darwin in Australia, sites we have used for our feasibility study. As an example, the calculations for the 70° radial, Figure 11, show mode conversion occurring over a small region within 2 Mm of the transmitter. This conversion results in mode 1 being dominant at 10.2 kHz at both locations, and at 13.6 kHz mode 2 dominant at Cubi Point and the modes equal at Darwin. At Yap, mode 1 is predicted dominant by a few dB, about 5 dB at 10.2 kHz, and 3 dB at 13.6 kHz. We have noted mode switching on occasion in the Yap data for Norway during the sunrise transition at 13.6 kHz and not at 10.2 kHz. Validating the mode conversion model for propagation over low conductivity terrain is not within our planned research. However, some very useful data could be acquired as a by product.

Trans-equatorial Propagation Mode Conversion: The trans-equatorial nighttime mode conversion is of prime interest for this feasibility study. In this section we will present general knowledge that led to our proposed research. Later we will describe the specific analysis we conducted during this study to assess feasibility for conducting and interpreting experiments.

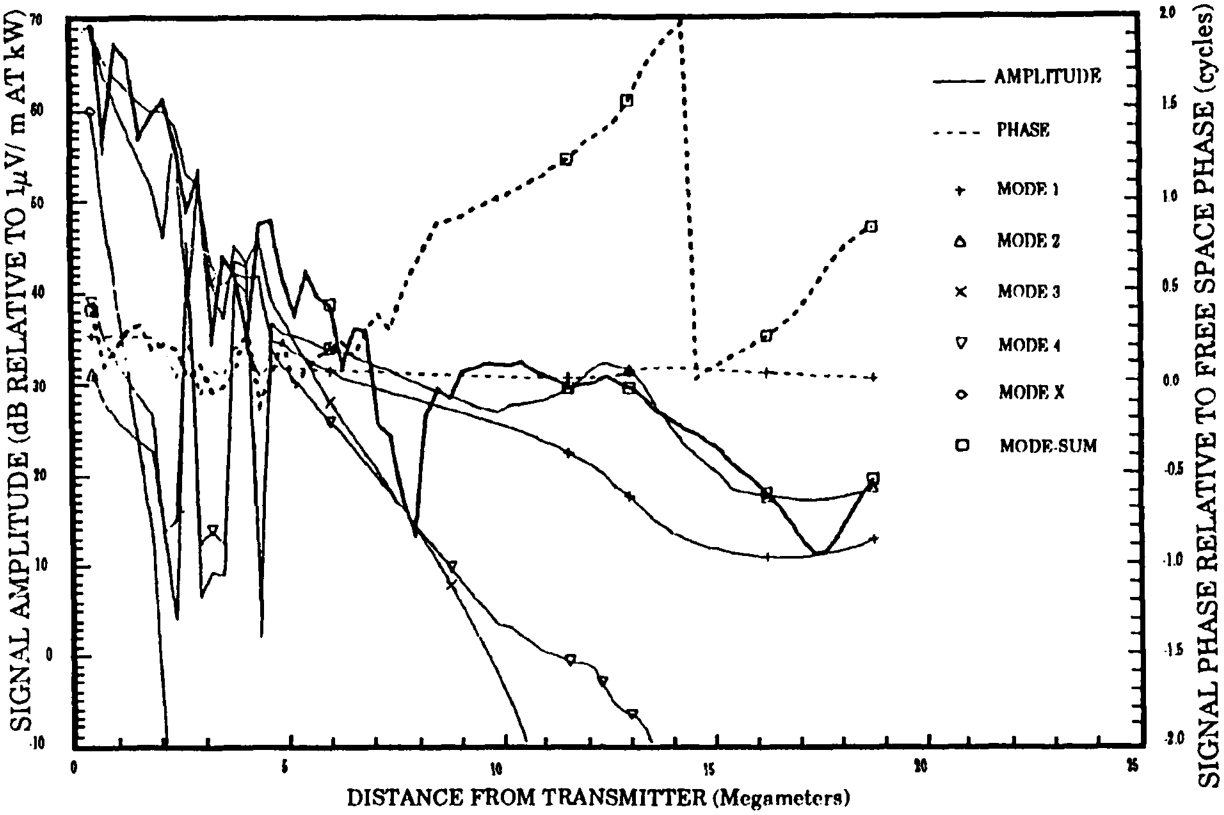

Figure 10(a). Norway 10.2 kHz Signal: Night, 340 Degree Radial

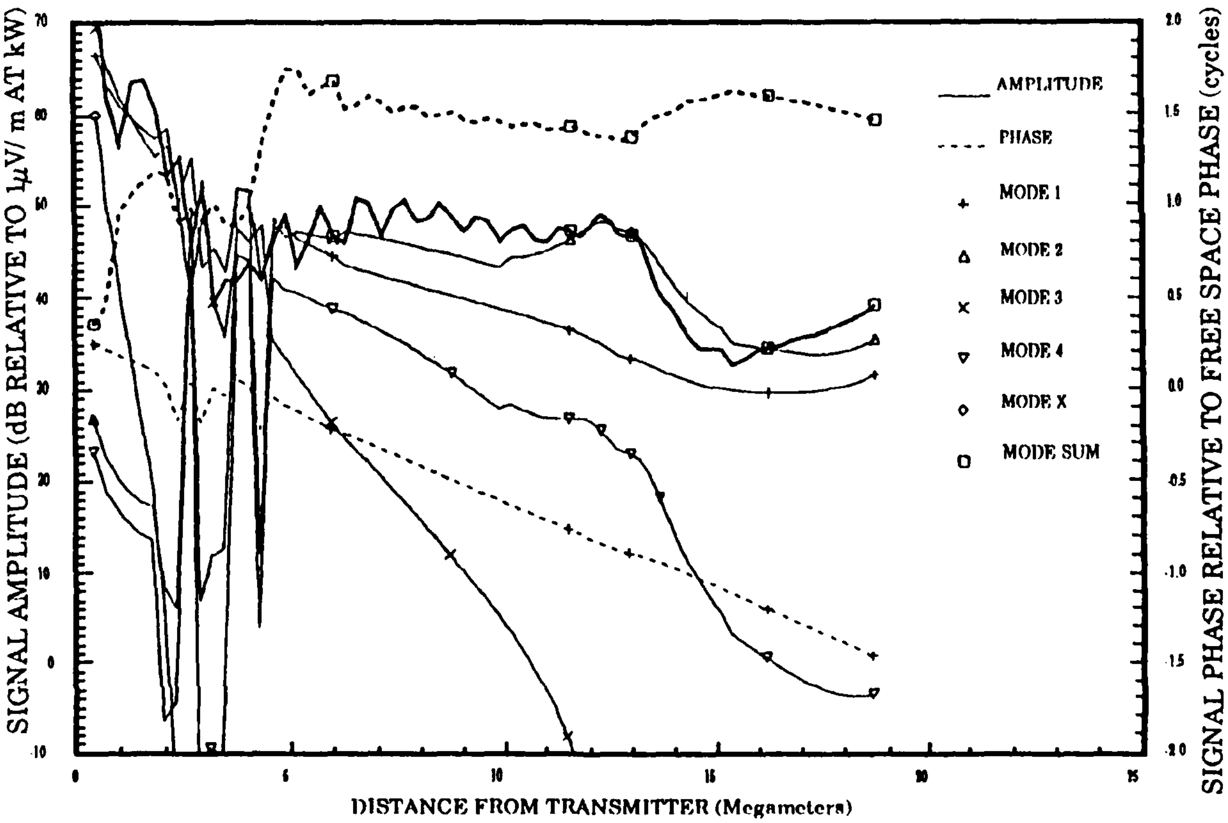

Figure 10(b). Norway 13.6 kHz Signal: Night, 340 Degree Radial

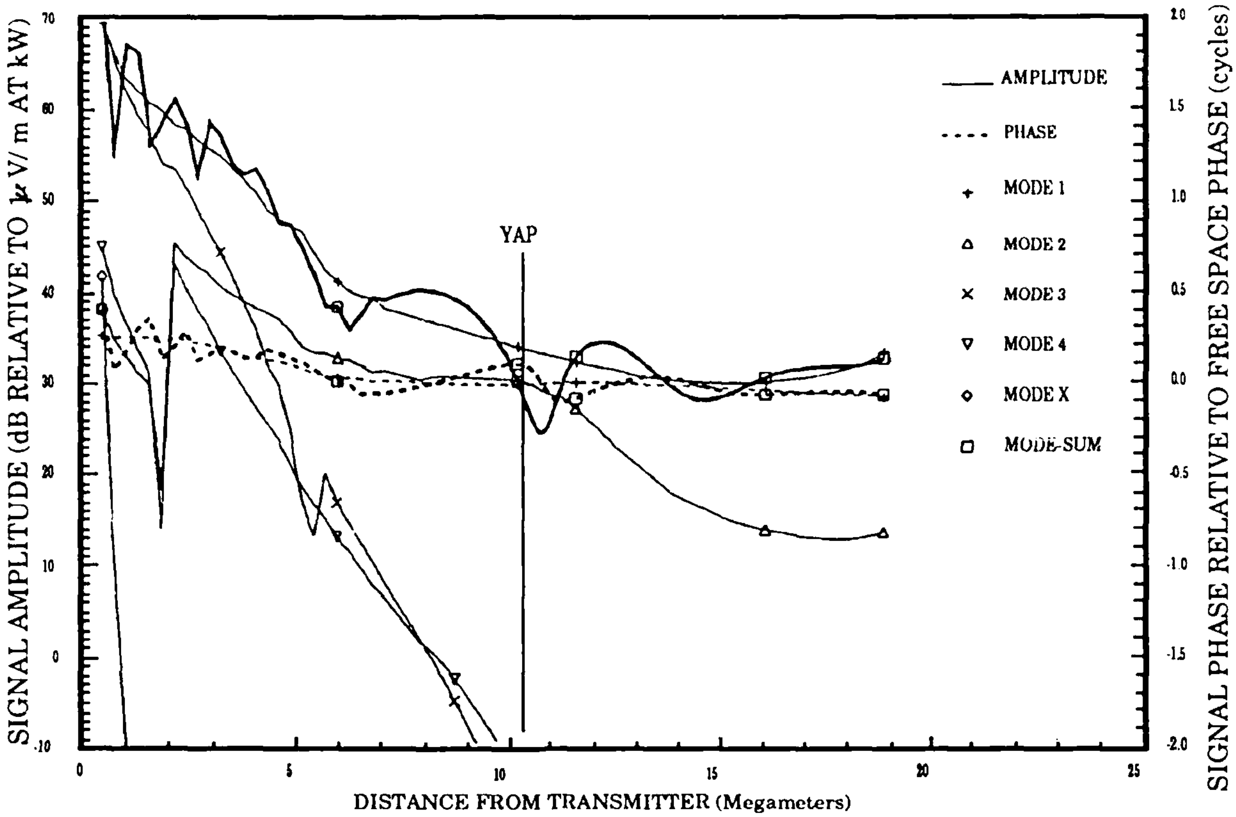

Figure 11(a). Norway10.2 kHz Signal: Night, 50 Degree Radial

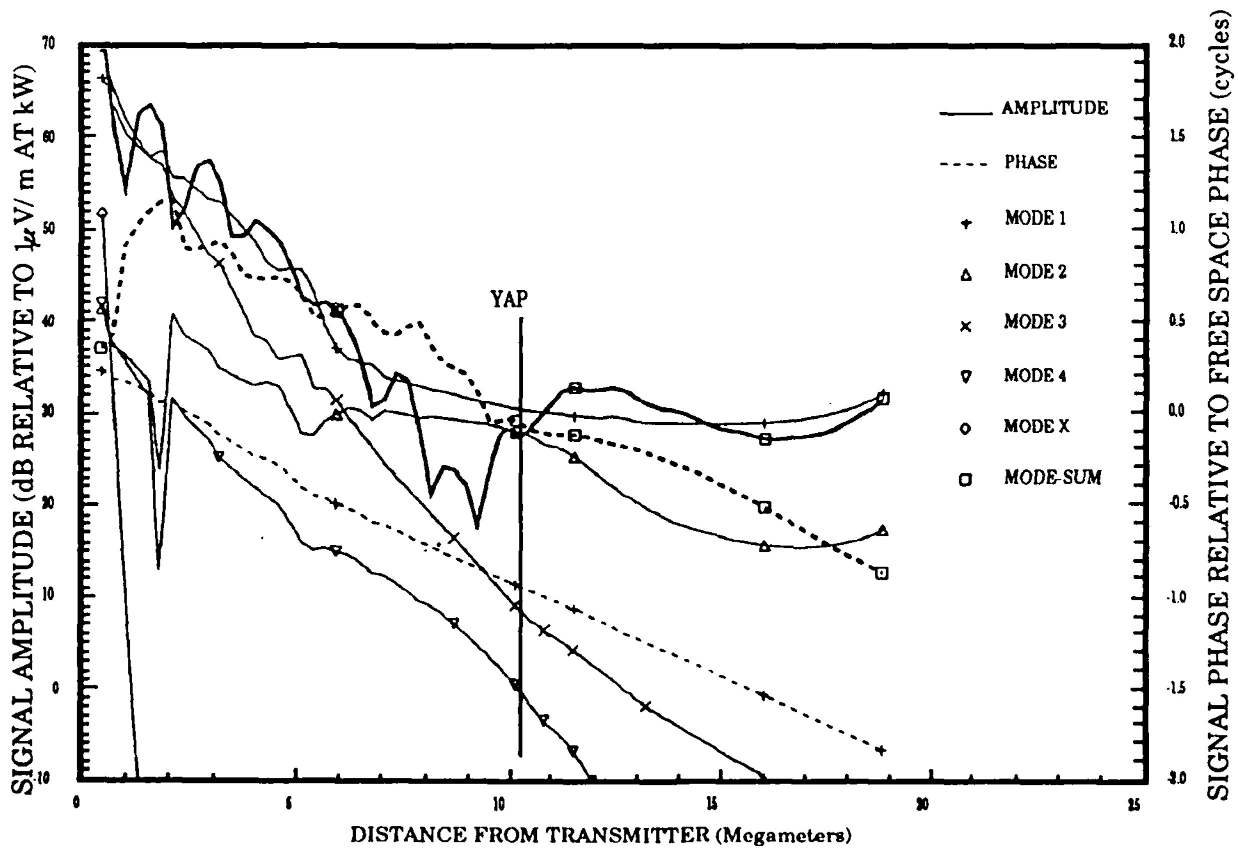

Figure 11(b). Norway 13.6 Signal: Night, 50 Degree Radial

While conducting a validation analysis of Omega navigation signal quality in the South Pacific for the U. S. Coast Guard Omega Navigation Systems Center (ONSCEN), we became fully aware of the prevalence and importance of trans-equatorial mode conversion. The signal propagation calculations used in this feasibility study [GUPTA, Ref. 2] were provided to us for that validation analysis. The equatorial zone of nighttime mode conversion is the result of interaction of the radiowave with the earth's magnetic field during ionosphere reflection. We need to learn more about the nature of this mode conversion process. But that is a story for later. Here we will describe our perspectives at the beginning of this feasibility study. From the calculations, we note that mode conversion occurs over a limited magnetic latitude range. We estimate approximately ±20°, but we need to check this value both by mode detailed calculations and experiment. Lynn [Ref. 11] reports ±20° magnetic latitude range. The conversion zone is also bounded by a range of propagation azimuths. The geographic heading of the radial at the transmitter for onset of mode conversion varies from about 190° to 210° and continues in a clockwise rotation until about 345° to 350°. This range of geographic headings for each boundary should map to a single magnetic heading for the propagating radiowave near the magnetic equator. The two bounding magnetic azimuths have yet to be determined.

The onset of mode conversion is very rapid; the mode conversion increases by over 20 dB in just a few degrees. Figure 12 shows the North Dakota Omega signal on a 200° propagation radial. The path crosses the magnetic equator at 5.9 Mm. At both 10.2 and 13.6 kHz the mode 2 signal has begun to build up, increasing over 10 dB from a non-conversion condition. At this heading the mode 2 signal at its peak value is still about 20 dB below the mode 1 signal. By a radial heading of 210°, shown in Figure 13, several modes have grown to be nearly equal to the mode 1 signal at the magnetic equator. We note that the weak modes become competitive with the dominant mode within a couple hundred kilometers. The width of the mode conversion zone along this radial is about 2.5 Mm. Within this distance interval, rapid exchange of energy is taking place between the modes. At onset of mode conversion, mode 2 is about 26 dB below mode 1 at 10.2 kHz. Upon exiting the conversion zone, mode 2 is dominant, being about 15 dB above mode 1. Mode 1 has lost energy to the other modes. At 13.6 kHz a similar buildup of mode 2 occurs, but on exiting the conversion region the two modes are of about equal amplitude. By a radial of 224°, Figure 14, the

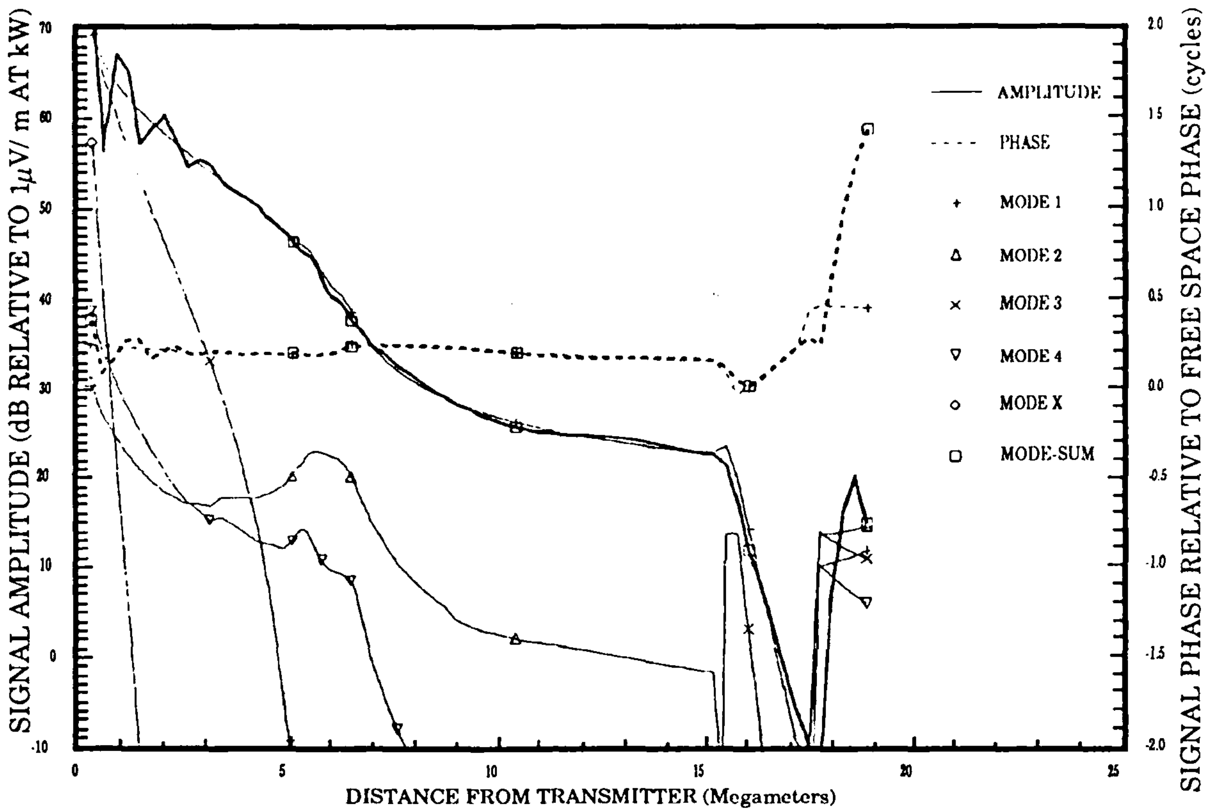

Figure 12(a). North Dakota 10.2 kHz Signal: Night, 200 Degree Radial

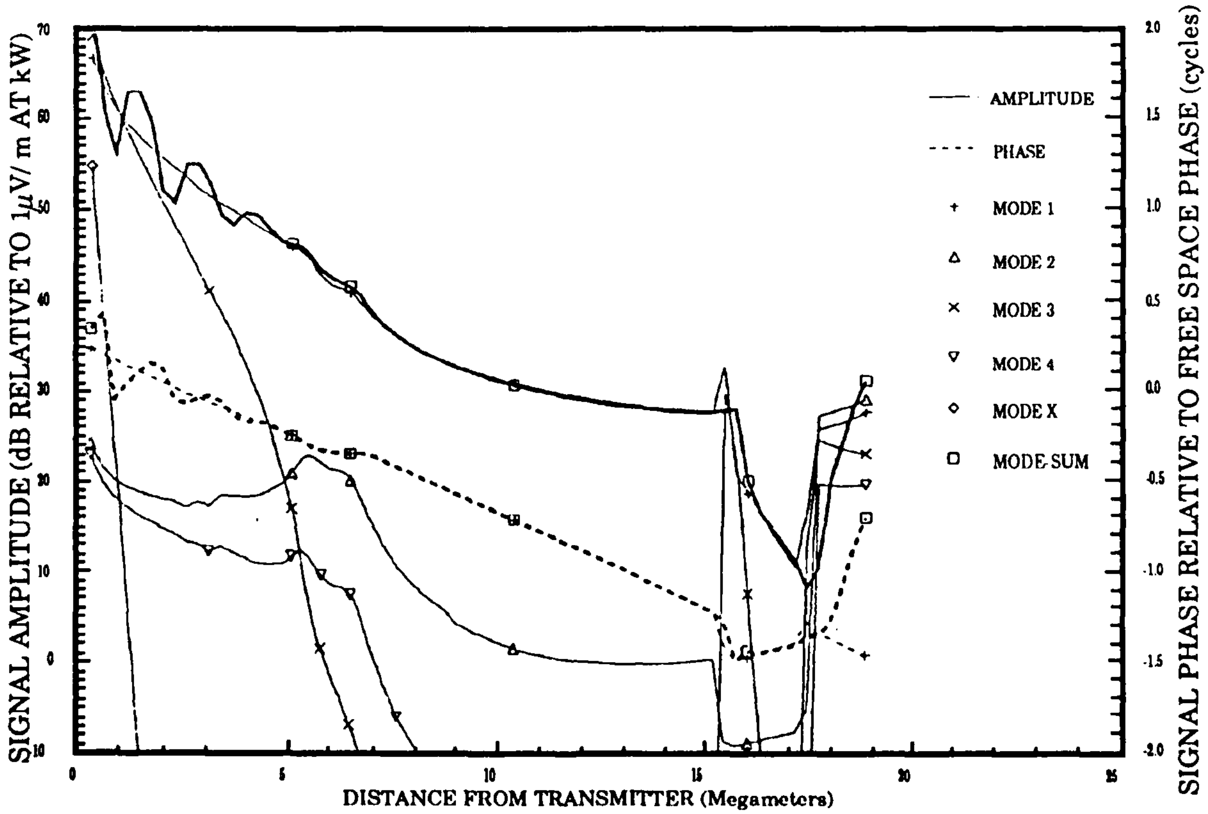

Figure 12(b). North Dakota 13.6 kHz Signal: Night, 200 Degree Radial

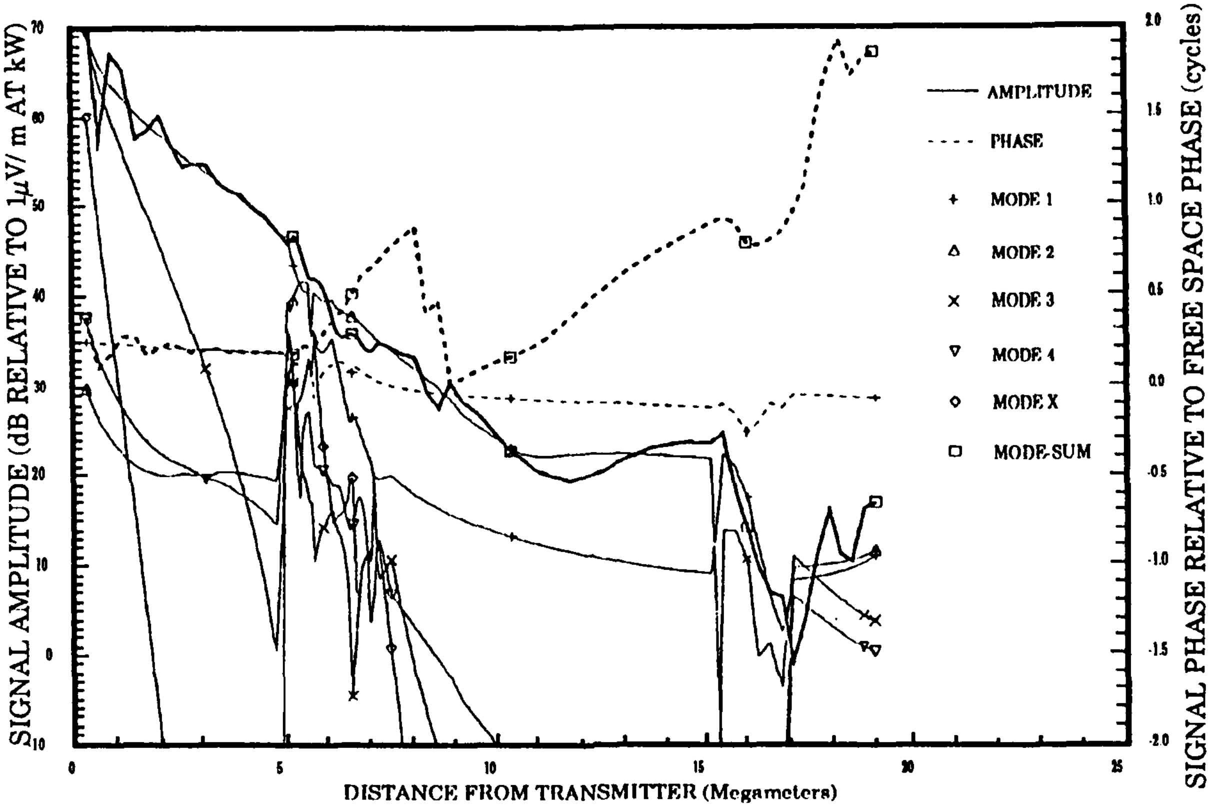

Figure 13(a). North Dakota 10.2 kHz Signal: Night, 210 Degree Radial

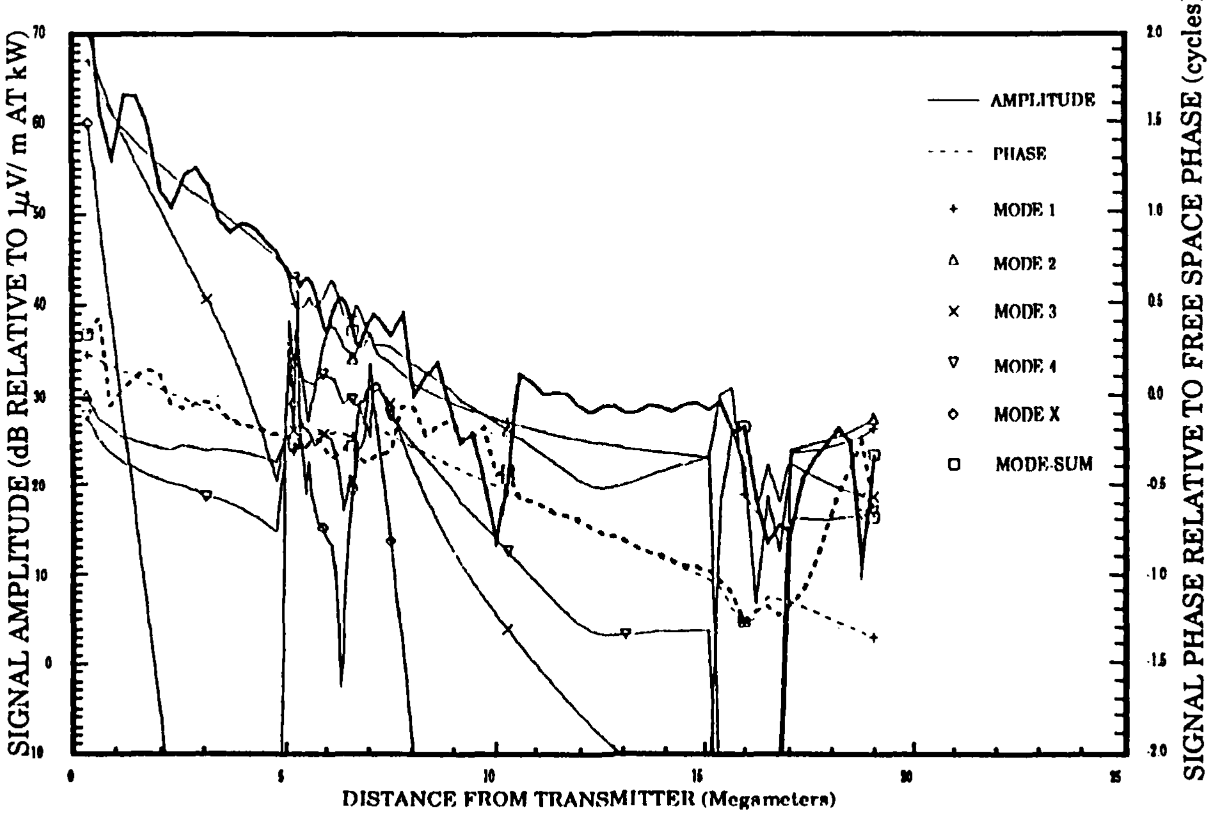

Figure 13(b). North Dakota 13.6 kHz Signal: Night, 210 Degree Radial

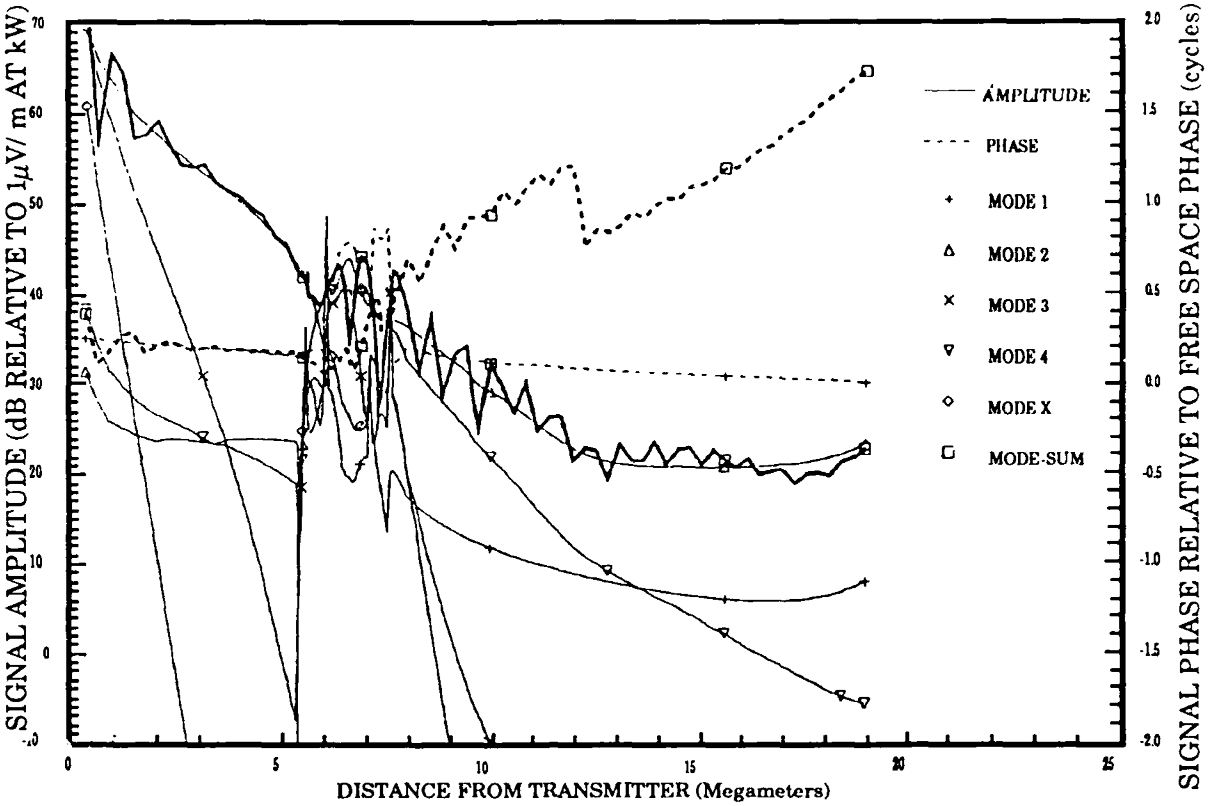

Figure 14(a). North Dakota 10.2 kHz Signal: Night, 224 Degree Radial

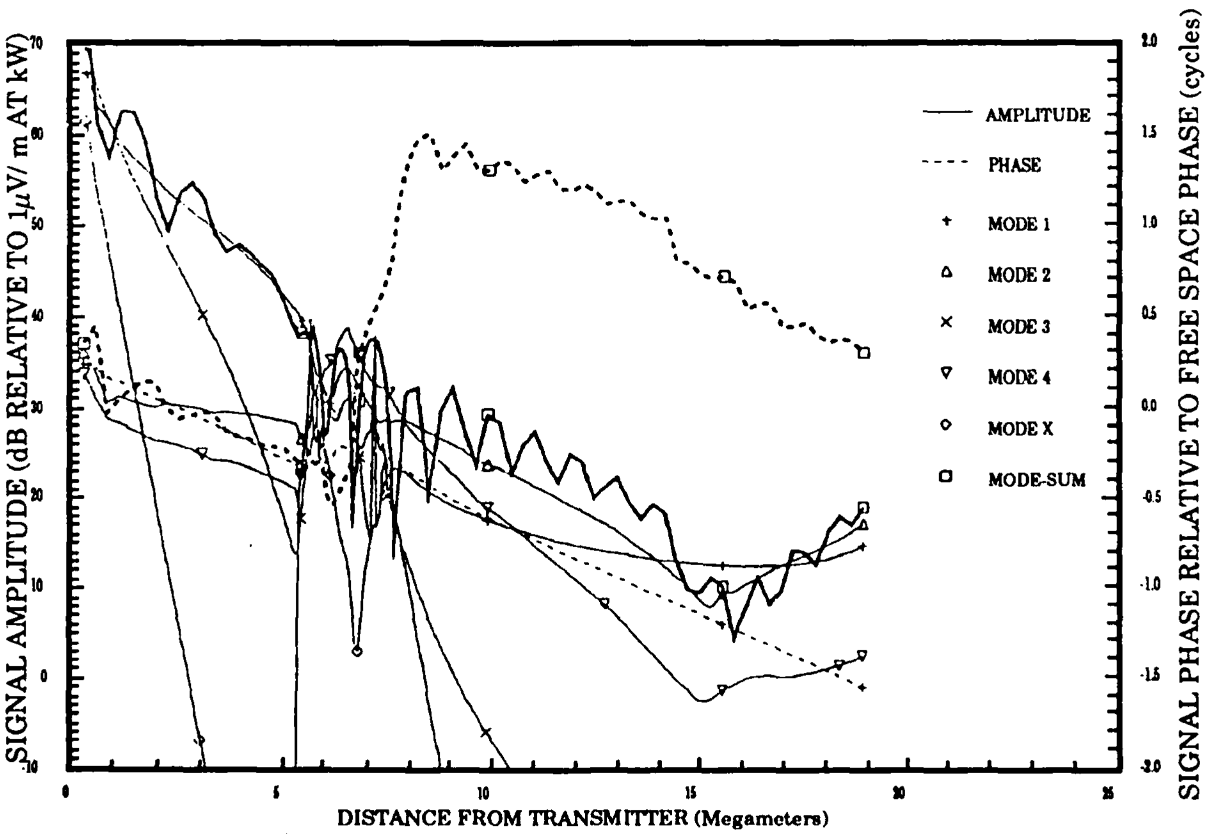

Figure 14(b). North Dakota 13.6 kHz Signal: Night, 224 Degree Radial

mode conversion is very strong with interaction occurring between many modes. Upon exiting the conversion region, at 10.2 kHz mode 1 is exceeded by both modes 2 and 4. At 13.6 kHz, these three modes remain close in amplitude from 8 to 12 Mm. Clearly these calculations show propagation effects that should be subject to examination and validation through measurements. For this research our interest is primarily in the equatorial zone mode conversion. However, the phenomena taking place in this zone can be better understood by making use of insights gained from other research.

2.1.3 MEASURED MODAL EFFECTS

Clearly, mathematical models predict strong modal interaction in nighttime propagation at near equatorial latitudes. We are well aware of the historical calculational problems in identifying and tracking modes. We are thus conditioned to be skeptical about how well calculations can predict when the products will be highly sensitive to ionosphere input parameters. We note, as shown in Table 1, that all nighttime calculations were made using a single exponential ionosphere; only the magnetic field and ground conductivity parameters are changed. These calculations are intended to represent a nominal or average condition. Our interests for this research are more in the dynamics and in the use of changing conditions to infer ionosphere properties.

Bickel [Ref. 12] in 1970 and others have reported that VLF propagation at nighttime within what we call the equatorial mode conversion zone is significantly different from that observed at mid-latitudes. When this zone is involved, attempts to fit a calculation model to VLF propagation data have not been fully successful, Ferguson [Ref. 13]. Ferguson also notes that large variations were recorded at fixed monitoring sites for several propagation paths, both during the course of a night and between nights. He noted from the fixed site data that the dates on which aircraft data was taken were less than ideal, and that from the large standard deviations involved ideal conditions may be rare. In reference to interpretation of propagation on a path from Hawaii to Wake Island, Ferguson states: "The recent 1977 data obtained on this path at the Omega frequencies show that even a temporally static model of the ionosphere cannot be used. Examination of the ground-site data presented in Reference 1 [our Ref. 14] shows that the Omega Hawaii signal amplitudes were quite variable at Guam during most

nights of the August-through-October recording period. This indicates that the ionospheric perturbations seem to exist most nights of the equinoctial months." Ferguson surmises from his analysis that "...any major disagreement between measured and calculated fields results from a lack of understanding of the geophysical processes that control the low-latitude ionosphere." These observations have important implications for our planned research. The good news is that the ionosphere dynamics we hope to study must be occurring, certainly the propagation situation is not yet well understood. The challenge is that analysis will have to be more sophisticated than previously conducted. We particularly take note that one set of ionosphere parameters is not likely to describe the propagation path. We are also encouraged by the findings of Ferguson that the propagation outside of the equatorial mode conversion zone was found to be well behaved, and generally it could be modeled using a single "best fit" exponential profile. Note that to this point we are still collecting and reporting evidence. Our use of this evidence will be described in the discussion of our experiment design and plan.

From conducting the South Pacific Omega Navigation Validation Analysis [Ref. 15] we have gained much insight into the characteristics of equatorial mode conversion. We highlight some important features using the Omega North Dakota signals measured at Tahiti. This is a 8.96 Mm path crossing the magnetic equator at an angle of about 203° magnetic. Using a Wavehop concept and assuming a 4 hop path, the last reflection region (4th), would be at about 12°S magnetic and the 3rd hop near 21°N. Given the distributed reflection properties of the VLF signal, this is not a clean case of a single reflection within the conversion zone, but it is the best available from the South Pacific monitoring sites. Phase records of 3 frequencies for 24-hour periods on two days are shown in Figure 15. Amplitude data was not analyzed because of limited accuracy. Note that the phase records are quite different between frequencies and for a given frequency between days. The complexity of these records can be contrasted by comparison with a signal containing primarily a single mode at all frequencies, such as the Hawaii signal recorded in Tahiti, Figure 16. In this figure the night and day/night transition times extend from 0200 to 1700 UT. Note that the phase traces are well behaved, though they change with time and between nights. Even a slight variation in the phase trace caused by propagation variations is similar at all frequencies.

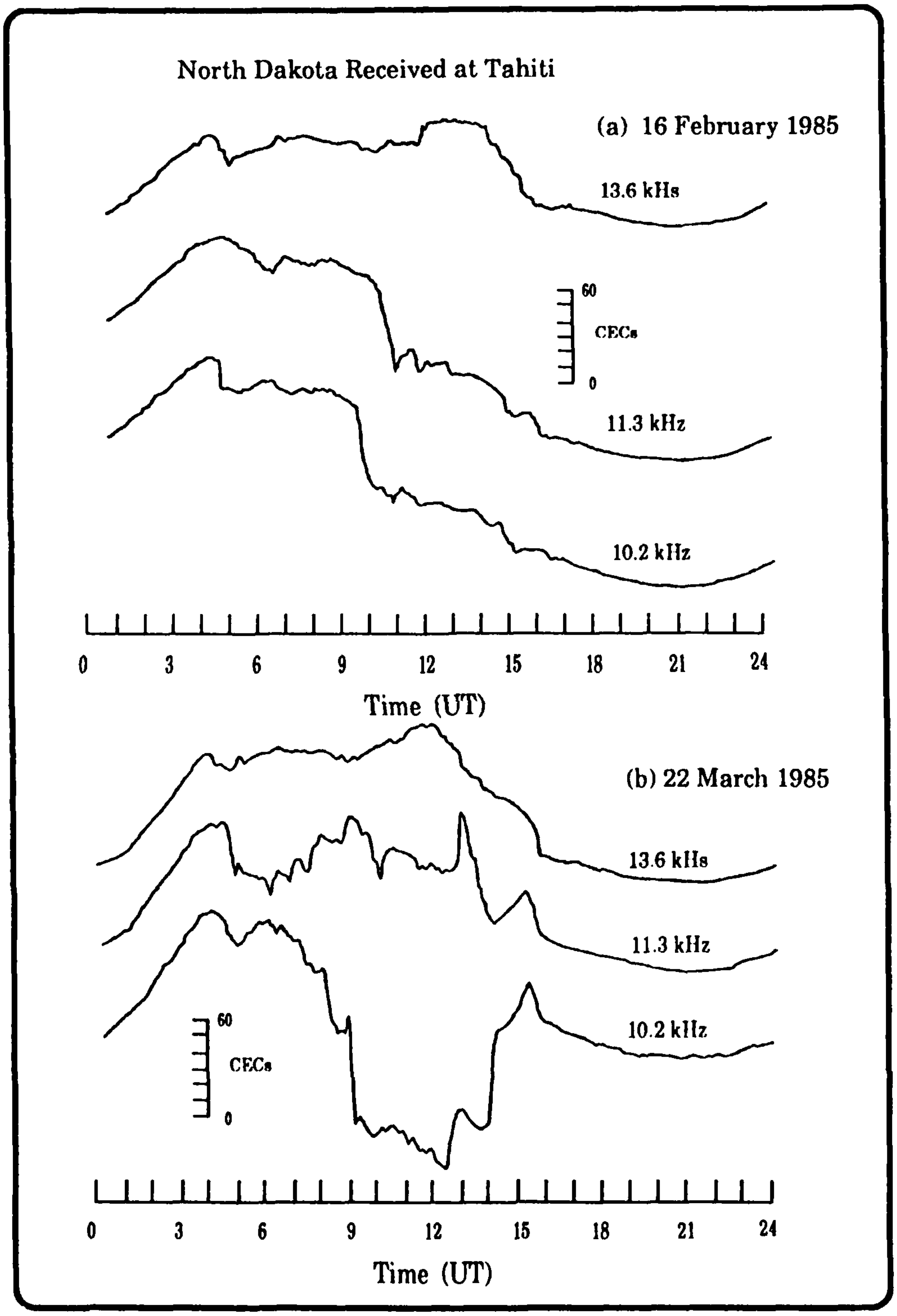

Figure 15. Example of Measured Phase When Strong Modal Competition is Present

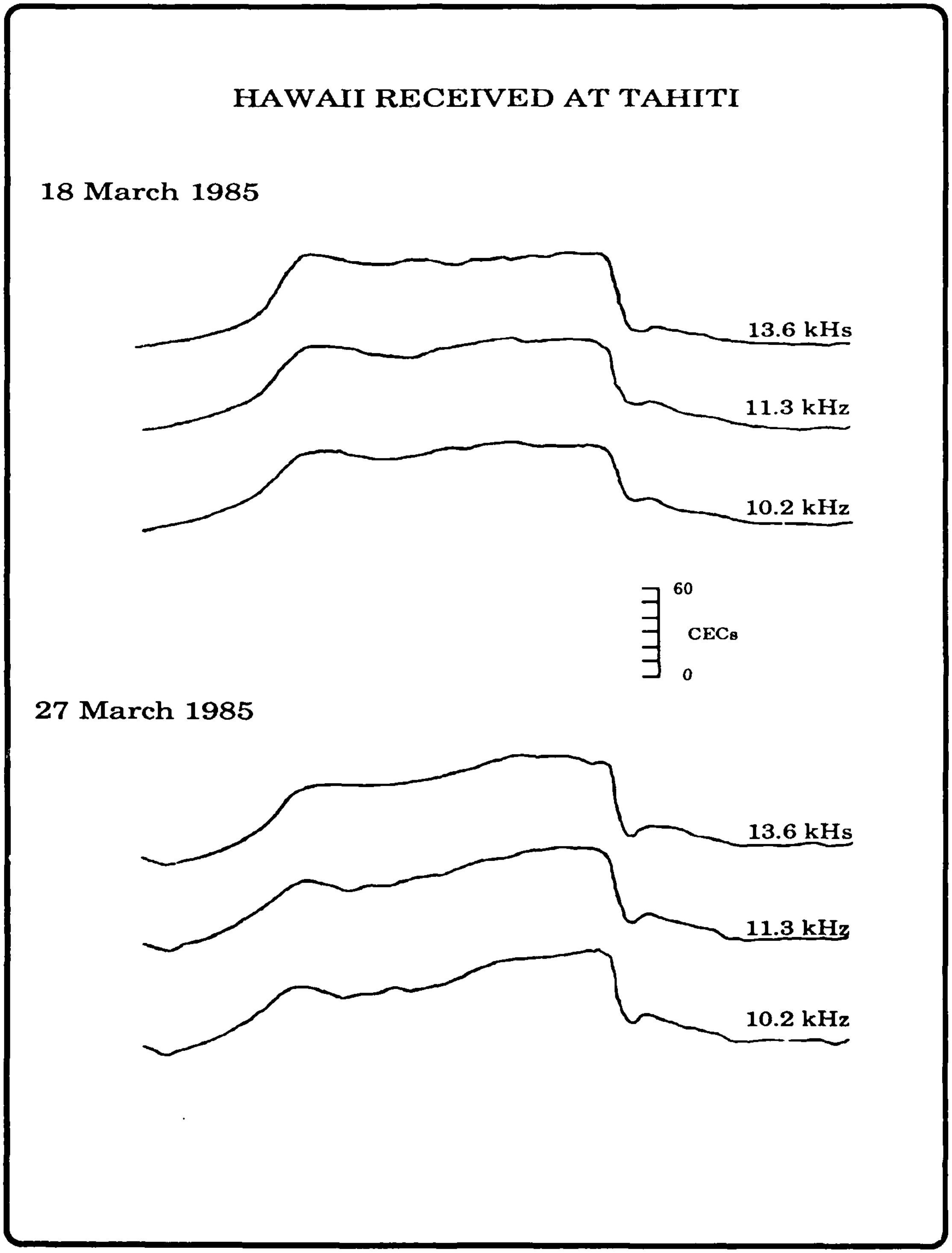

Figure 16. Example of Measured Phase When Mode 1 is Dominant

Returning to Figure 15, the daytime period, (the last 8 hours of the records) is very well behaved, clearly showing the solar zenith angle effect. The sunset phase transition looks quite normal, indicating a clean mode 1 signal until after 0300 UT. By estimating the relaxation time of the ionosphere during sunset from steep incidence sounder data on a single mode path, we can infer as to how close the ionosphere at the last reflection point is to a nominal nighttime value. The calculation for the 200° radial should work well enough. Our estimate is that most of the path had reached a nighttime reflection height, but that the portion in the conversion zone had transitioned about 80 percent of the change to early night conditions. Following the sunset transition, evidence of the appearance of a second mode is very marked, by the initiation of a phase advance on all three frequencies for both days. The timing indicates that mode conversion requires conditions very close to a nighttime ionosphere. The calculations, Figure 13, show for 10.2 kHz that mode 2 becomes about 15 dB stronger than mode 1. Other modes are insignificant. The composite phase is essentially the same as the mode 1 phase. For 13.6 kHz modes 1 and 2 are predicted about equal and the composite phase would be advanced about 25 Centicycles (CECs). The data indicate just the opposite. For both nights the 13.6 kHz phase follows about the pattern expected for a clean mode 1. Some mode 2 is evident however. Halfway though the night the 10.2 kHz phase undergoes a major advance. On 16 February the 11.3 kHz signal follows the 10.2 kHz large phase change, but this change does not begin until the 10.2 kHz change is completed. At 13.6 kHz small perturbations are associated with the 10.2 and 11.3 kHz onset times, and a 30 CEC change in the reverse direction occurs about one hour after the end of the major 11.3 kHz transition. For the 22nd of March a perturbation also occurs during the second half of the night record.

At first glance the records for these two days look very different. Actually until 1200 UT the 10.2 and 13.6 kHz records are quite similar between days. The major difference is the phase response of 11.3 kHz to the perturbations. We suspect that most of the apparent difference is due to a slight physical difference for the perturbation, probably size and location. Extensive use will have to be made of the modeling tools to interpret these phase records. An important concern is that the model poorly predicts the relative modal content of the 10.2 and 13.6 kHz signals. Actually these two samples are quite dramatic phase perturbations, but certainly not highly unusual. Referring to the entire data set of North Dakota at

Tahiti, a wide variety of modal interaction conditions is depicted. Twenty-four hour segments can be found that appear almost free of higher mode signals, that have moderate modal content, and that are are similar in complexity to the above examples. Such variety is welcome, because we can begin analysis using benign conditions and then with increasing experience undertake more complex situations. The analysis will, however, be quite limited without both better data and more flexible analysis tools. Major drawbacks of the presently available Omega data are that only the measured phase is suitable for analysis and the measurement sites are widely separated. A potential advantage is that each station transmits at four frequencies between 10.2 and 13.6 kHz.

2.2 A RESEARCH OPPORTUNITY

To date modal interference effects have been treated largely as a problem. The mind set of the VLF propagation research community, with respect to modal effects, has been to understand, predict, and mitigate the system performance problems resulting from modal effects. Given the sources of funding this is understandable. However, there is also an opportunity. The opportunity is that the strong interactions of many modes should greatly enhance the information content of a VLF signal regarding propagation parameters, and hence geophysical properties of the ionosphere D-region. Exploring this opportunity is the focus of this feasibility study and of the overall research project. We believe that this new mind set, while focused on studying ionosphere dynamics, can contribute to solving the problem.

A unique opportunity for conducting geophysical research has been identified because of the good geometric and signal conditions that exist in the Western Equatorial Pacific. In particular, many available VLF signals are expected to undergo nighttime mode conversion, 16 Omega navigation signals and at least three signals from VLF communications transmitters. Judicious placement of a few measurement systems in this region should yield a wealth of data. We were fortunate that data obtained in the Omega navigation validation program could help determine what to expect and how to design measurements. Since the research products are expected to directly benefit Omega, we expect that identification with Omega, an international system, will aid in making contacts for

cooperative efforts and establishment of measurement sites.

Consequently a research project was proposed that would consist of several phases: feasibility studies, experiment planning and design, experiment implementation, and experimentation including data analysis and interpretation. The feasibility studies, conducted in Phase One, are the subject of this report.

3.0 EXPERIMENTAL CONCEPT FEASIBILITY ANALYSIS

The essence of this project is based on our contention that, first the VLF mode conversion occurring in trans-equatorial propagation contains valuable information on the characteristics of the interacting ionosphere, and second, that more information can be derived with than without mode conversion. It is this contention and the opportunity it presents to study a very interesting ionospheric region (one very difficult to study otherwise) that has led to our undertaking this project. Our view is that the findings of this feasibility study strongly support the original hypothesis that the topic offers a significant research opportunity. In this section we will present an overview of the information derived during the Phase One effort.

The material to be presented will be in three parts: (1) a summary of feasibility studies and experiment design, (2) evidence for ionosphere phenomena of great interest for investigation, and (3) exploration of techniques for data analysis and derivation of ionosphere parameters.

3.1 EXPERIMENT CONCEPT DEVELOPMENT

Section 2.0 BACKGROUND of this report presented historical evidence for the phenomenon of rapid, strong VLF propagation modal conversion during nighttime in the equatorial zone. A rationale was also presented for utilizing this phenomenon to create a new opportunity for investigating the dynamic properties of the nighttime D-region ionosphere. Our preliminary analysis had led to the possibility of conducting a series of experiments in the general vicinity of the South China Sea and adjacent land areas. This experimental concept is developed further in this section.

As suggested in the Section 2.0 BACKGROUND, the far Western Pacific area extending from Manila westward beyond Sumatra produces a unique opportunity to use modal conversion. At least 23 VLF transmissions affected by modal structure traverse the area. These transmissions are from five Omega transmitters located in Hawaii, North Dakota, Argentina, Australia and Japan (4 frequencies each), and from three communications transmitters located in Hawaii, Japan and Australia. Other low frequency (LF) transmissions may be available. The Argentina signal, while predicted modal, also traverses Antarctica for most of this region. The Argentina signal may not be very useful for research purposes. Other advantages include past research conducted by the Australians [LYNN, Ref. 7 and 11], the Japanese [TAGUCHI, Ref. 16], a data base from the U. S. Coast Guard Omega Validation Program, investigations conducted by the Naval Ocean System Center [BICKEL, Ref. 12 and FERGUSON, Ref. 13], the installation of a Differential Omega system in this region [SWANSON, private communication], and the ready accessibility for monitoring sites.

3.1.1 MODAL CONVERSION ZONE PREDICTION

An important first effort was to establish more closely the predicted zones where mode conversion occurs. This was a two phase process. First, calculations were used to establish theoretical boundaries, and then data from Coast Guard Omega monitoring sites was examined to check the predicted boundaries. A sample calculation is shown in Figure 17 of the Omega Australia signal propagating on a 320° radial. The zone of modal interaction, as detected by a receiver on the ground, extends from about 5 to 7.5 Mm. These modal conversion zones, as established by the calculations, approximately follow the ±20 degree magnetic latitudes. The modal conversion zones derived from the calculations of Gupta, are shown in Figures 18, 19 and 20 for respectively, the Hawaii, Australia and Japan Omega signals. Note that the Hawaii signal conversion zone covers a broad swath originating to the east of the 180° meridian and extending beyond 90° east longitude. For the Australia signal, the eastern boundary of the conversion zone is approximately along the 153° geographic radial from the transmitter. The western boundary extends beyond the edge of this figure. The north and south boundaries do not seem to follow precisely either a geographic or magnetic latitude. The width of the boundary is about 30° in magnetic latitude and

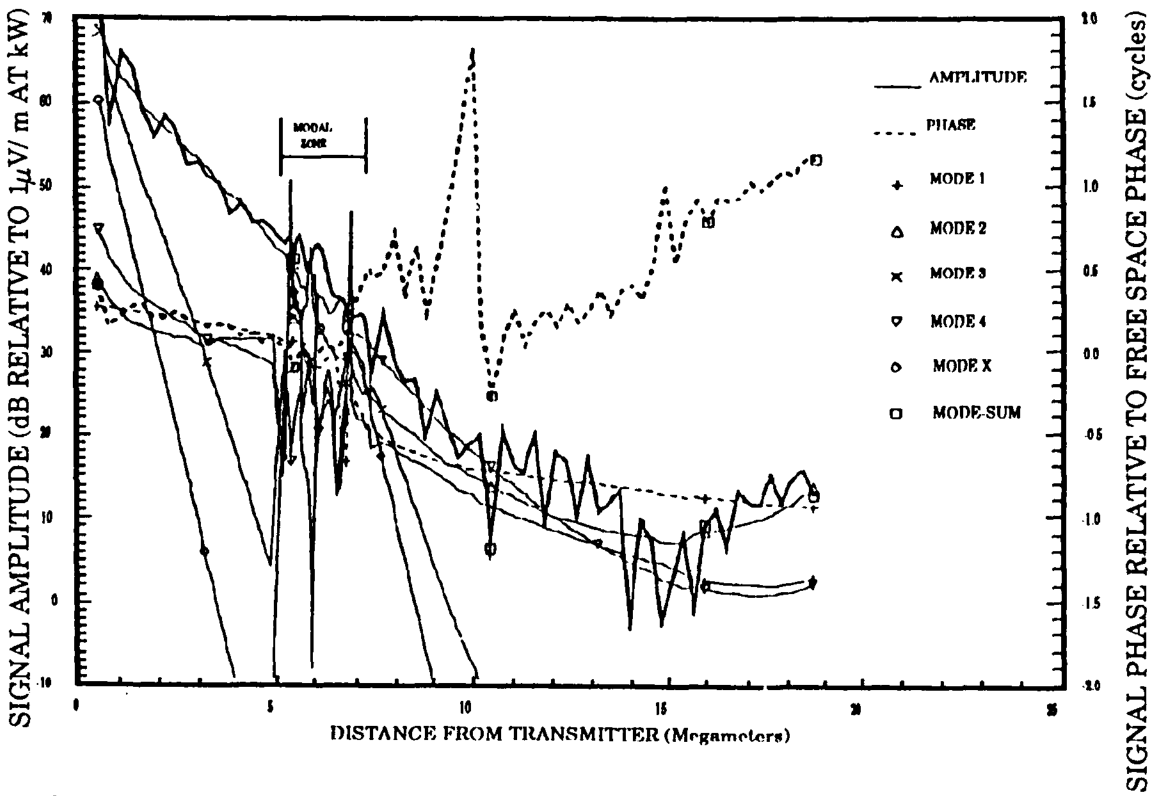

Figure 17(a). Australia 10.2 kHz Signal: Night, 320 Degree Radial

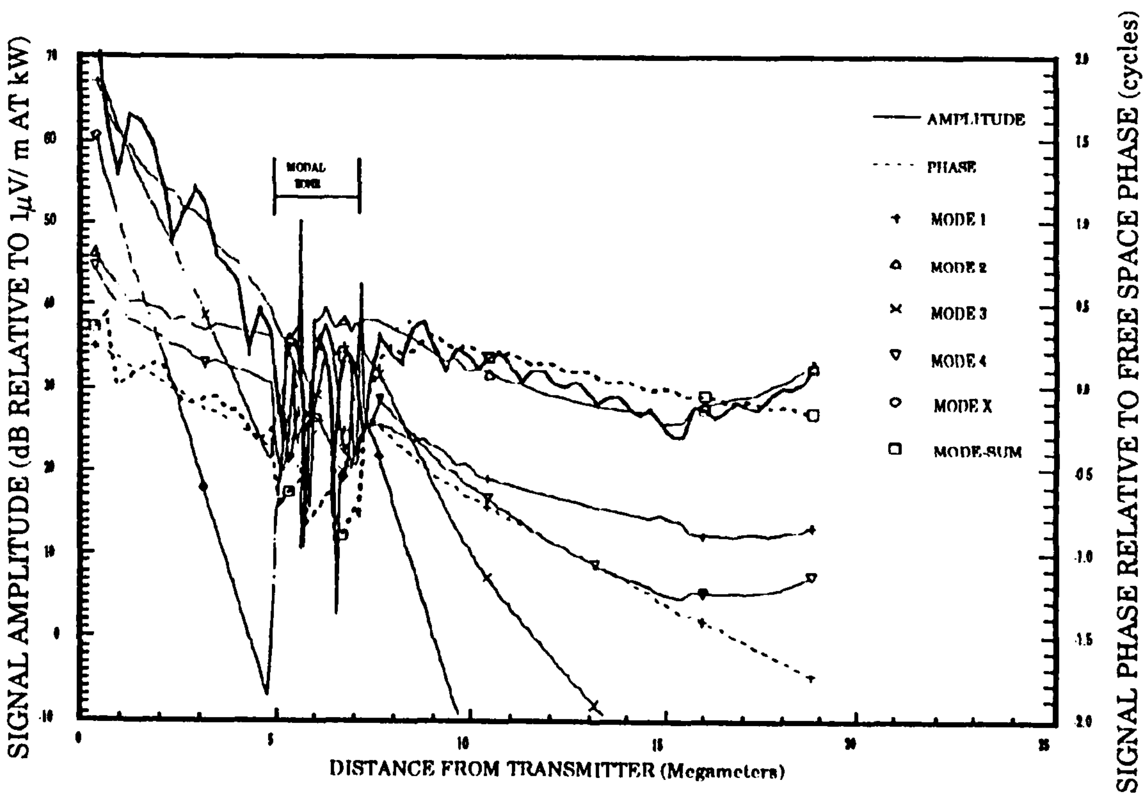

Figure 17(b). Australia 13.6 kHz Signal: Night, 320 Degree Radial

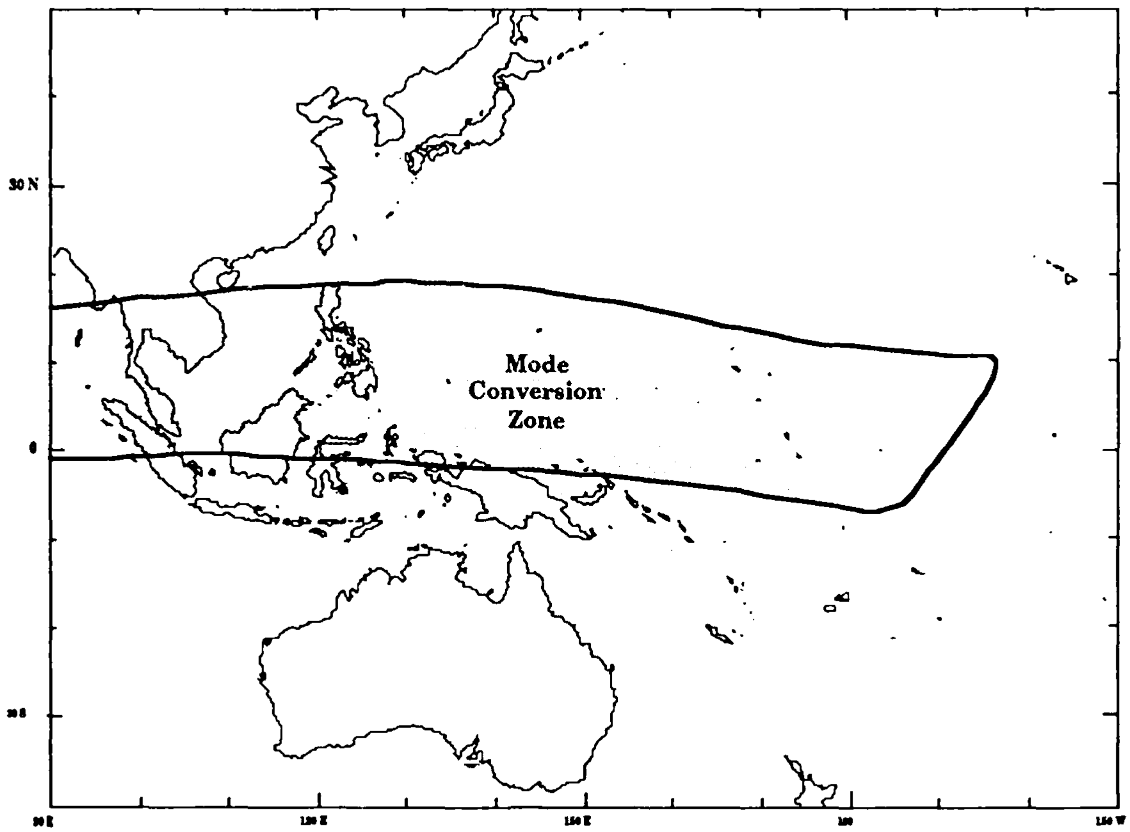

Figure 18. Predicted Mode Conversion Zone, Hawaii

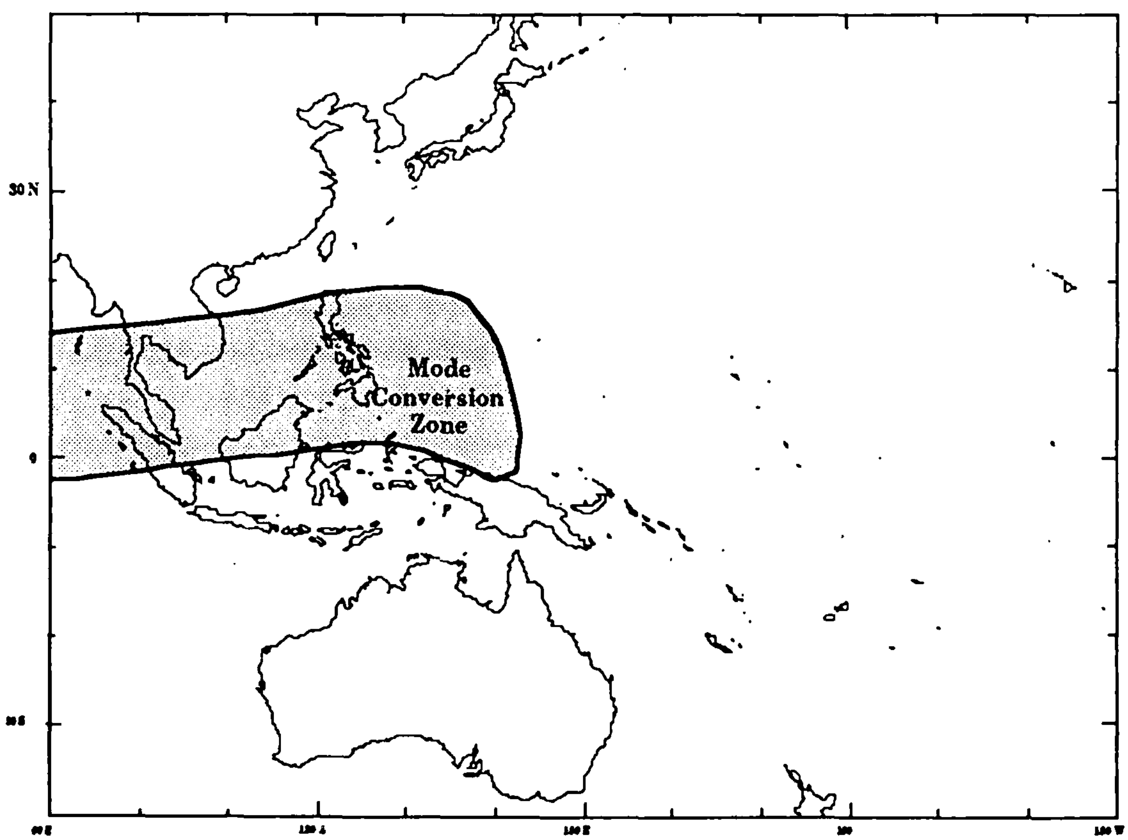

Figure 19. Predicted Mode Conversion Zone, Australia

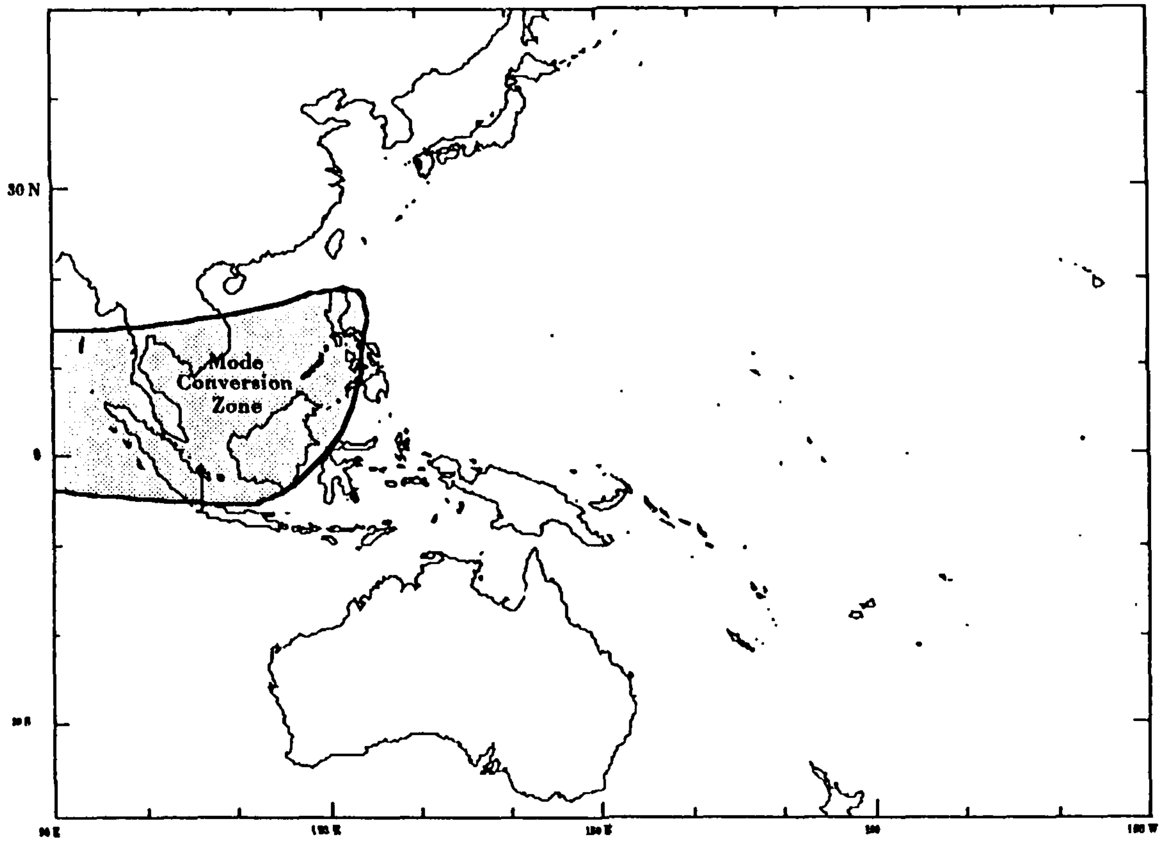

Figure 20. Predicted Mode Conversion Zone, Japan

moves southward going from east to west. The Japan signal eastern conversion zone boundary lies approximately along the 190° geographic radial from the transmitter. The western boundary is beyond the figure. The northern boundary is predicted to dip from 20° north magnetic latitude to about 15° with westward movement along the boundary. The southern boundary closely follows the 30° south magnetic latitude line.

3.1.2 MODAL CONVERSION ZONE VALIDATION

A second step was to test the validity of the predicted modal conversion zones. Our interests are to ensure that measurement sites can be selected which monitor propagation from either inside or outside of the conversion zones. Knowing the degree of zone overlap from the transmitters also allows for better placement of monitors. Data acquired for the Western Pacific Omega Validation is examined to determine if modal effects could be observed. If so, they determine

how the modal effects correspond to the predicted boundaries. While the data base was of very limited value, several important clues were derived to suggest that the theoretical model was adequate for experimental design purposes. Data from five flight radials within or near the composite conversion zones was examined. As expected, the results were mixed, with much of the data difficult to interpret. The data showed no evidence, indeterminate evidence and pronounced evidence of mode conversion. Our previous experience was that strong modal conversion occurs about thirty percent of the nights. When modal effects were noted, the receiver was within the predicted zone for the received station. An excellent example of observed modal effects on aircraft flight data is shown in Figure 21. This figure is an amplitude plot of the Australia signal as recorded on a round-trip flight from Hong Kong to the southern tip of the Philippines and return. The modal effects are evidenced by the signal amplitude fluctuation with distance. A correspondence exists between the positions of signal maxima and minima across the recorded frequencies. The maximum distance of observed modal effects with a high fade period coincides well on each flight leg with the predicted northern conversion zone boundary. We attribute the different signatures at corresponding frequencies for each flight leg to the buildup of modal conversion as the night progressed.

Data was also acquired from four fixed sites within or near the conversion zone using Omega receivers: at Clark Air Force Base in the Philippines, on Yap Island, at Darwin in Australia, and at Singapore. These receivers are designed to measure phase difference, so only short term stability is required for the phase measuring system. The recorded phase records had quite a bit of drift, typically five or more cycles per day, that mask modal effects. Techniques for semi-automatically removing the drift effects were devised to confirm that the prediction model is adequate for our experiment design. We expect that prediction refinements will be desired for navigation use. To summarize, Darwin data shows no mode conversion effects for the Australia signal. At Clark Air Force Base, modal effects have been noted for at least three signals, Hawaii, Australia and Japan. Singapore shows modal effects, at least for Japan. The Singapore data contains many periods of strong interference and much more work will be required to validate modal effects for Australia and Hawaii. The observed modal effects show dynamic activity at all locations.

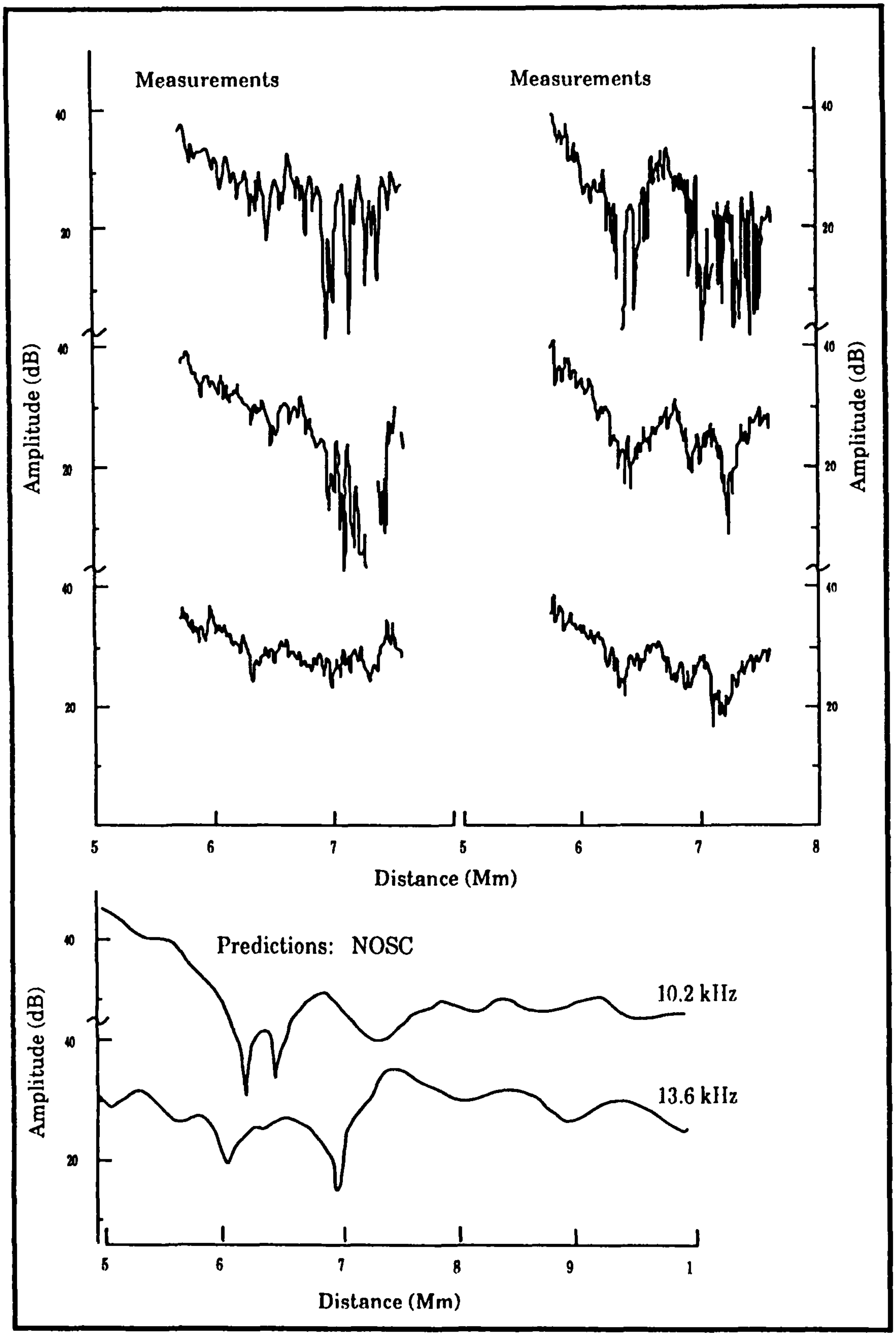

Figure 21. Australia Signal Modal Effects, Flight Data

3.1.3 MEASUREMENT EVIDENCE FOR MODE CONVERSION

A few examples of analyzed data will be shown to illustrate the support for predictions and the indicated modal effects. Two stations, Liberia and La Reunion are predicted to have a clean mode 1 signal in this region. These signals should provide a good reference for establishing a perspective regarding the identification of modal effects. In Figure 22 we show the La Reunion signals for a seven-day interval, 01 to 08 January 1987. Note that the records for the three frequencies generally track quite closely, but not always. At nighttime (right half of the figure) some differences can be seen in the wiggles of the traces. However, relative to modal conversion effects these differences are small.

Our model places Cubi Point, in the Philippines, at a good location for detecting modal effects on the Australia signal. In Figure 23 we show the 10.2 kHz Australia signal for the same seven-day interval. The phase record differs so much between frequencies and days that we chose not to interleave the frequencies. Figures 24, 25 and 26 show reduced versions of the plots for each of the frequencies. The vertical offsets between days differs from day to day to accommodate the phase records. Note that the sunset and sunrise times typically incur phase perturbations as described by Lynn [Ref. 11] and Taguchi [Ref. 16]. Their interpretation (and we agree) is that a different mode is taking over dominance between day and night. For this particular set of records, the nighttime segment, after mode dominance switching, is relatively quiet. The record is not as quiet, however, as is typical for a path that does not enter the mode conversion zone. The 13.6 kHz phase has many events of large phase fluctuations. We tentatively interpret these fluctuations as a tendency to switch back to mode 1. The records for the first two days show a perturbation beginning just after local midnight that appears to cause the 13.6 kHz signal to transition to mode 1 by the onset of sunrise. On the seventh day a perturbation occurs before midnight that moves the 13.6 kHz phase in the opposite direction and then returns. This perturbation is not nearly so evident on the two lower frequencies. It can be detected, however, when the three records are intercompared. The early night record for the 5th day is interesting for the direction and magnitude of the large phase excursion. A phase advance occurs at 10.2 kHz, a large retardation at 11.3 kHz, and at 13.6 kHz a retardation about equal to the 10.2 kHz advance. The 11.3 kHz phase breaks from the sunset curve almost an hour earlier than the

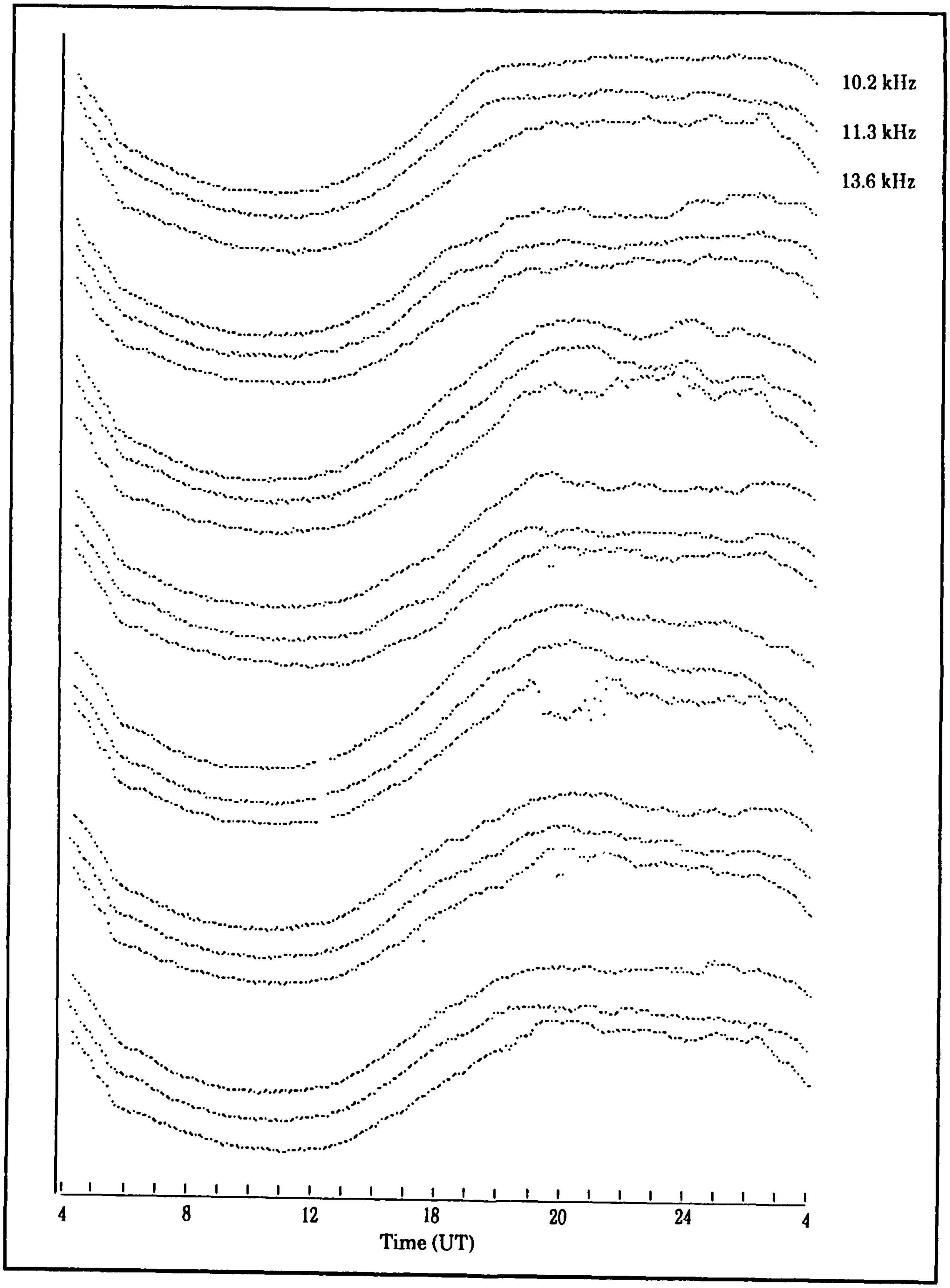

Figure 22. 10.2, 11.3, 13.6 kHz Phase, La Reunion at Cubi 01–07 January 1987

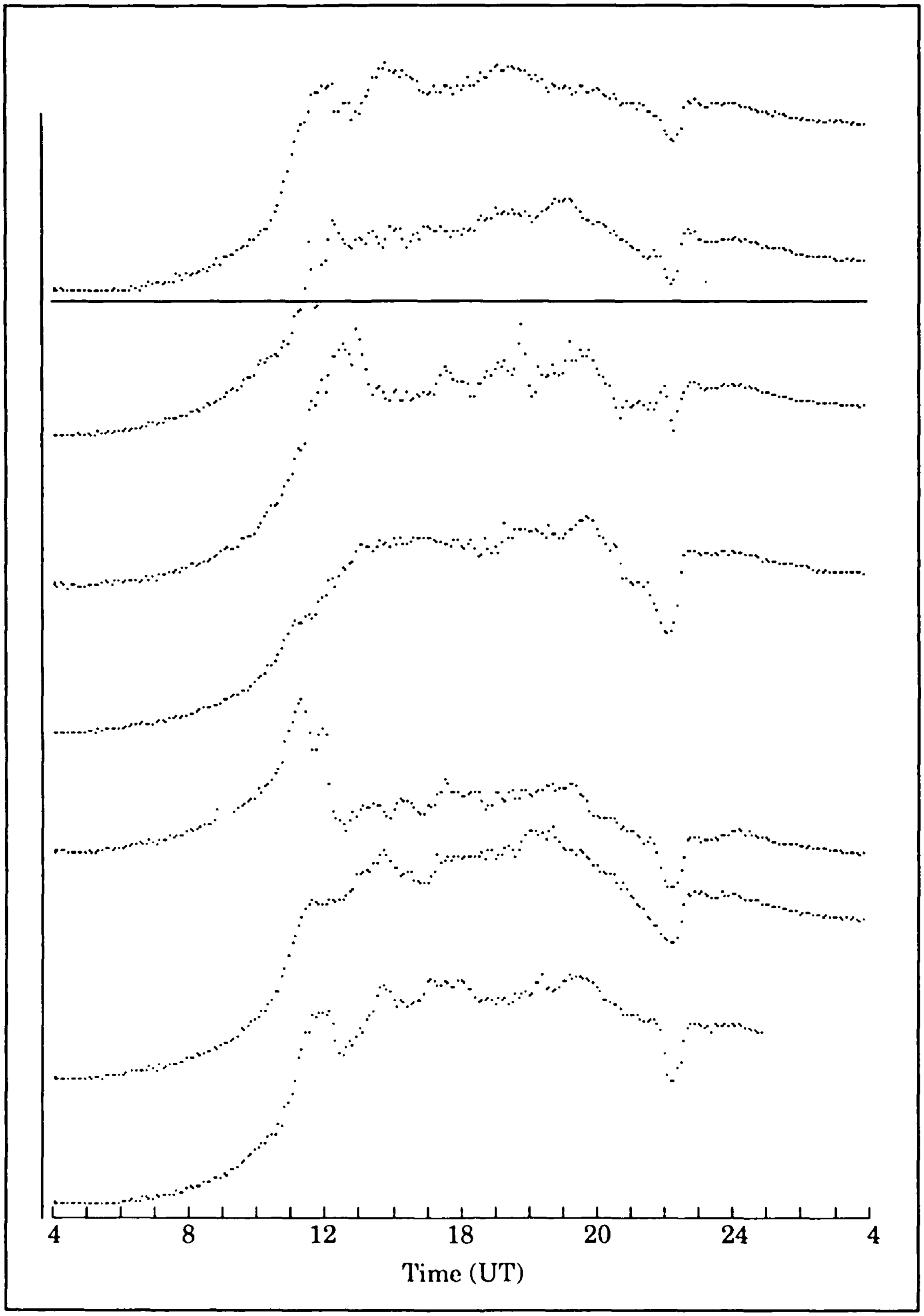

Figure 23. 10.2 kHz Phase, Australia at Cubi Point 01–07 January 1987

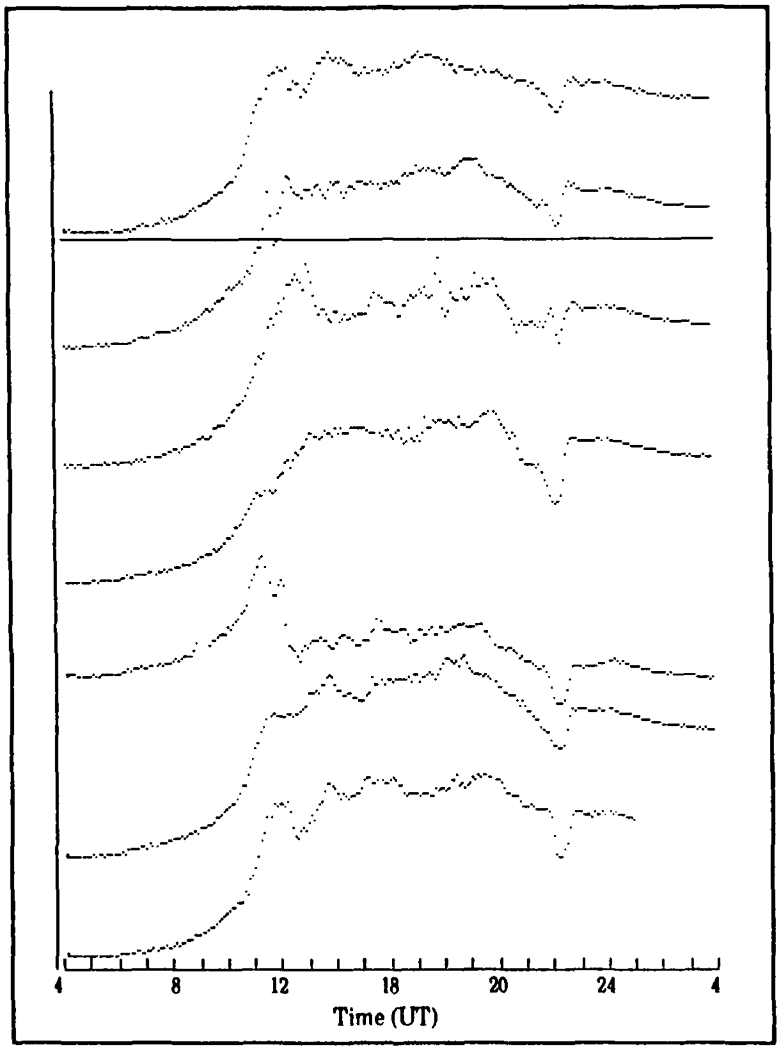

Figure 24. 10.2 kHz Phase, Australia at Cubi Point 01–07 January 1987

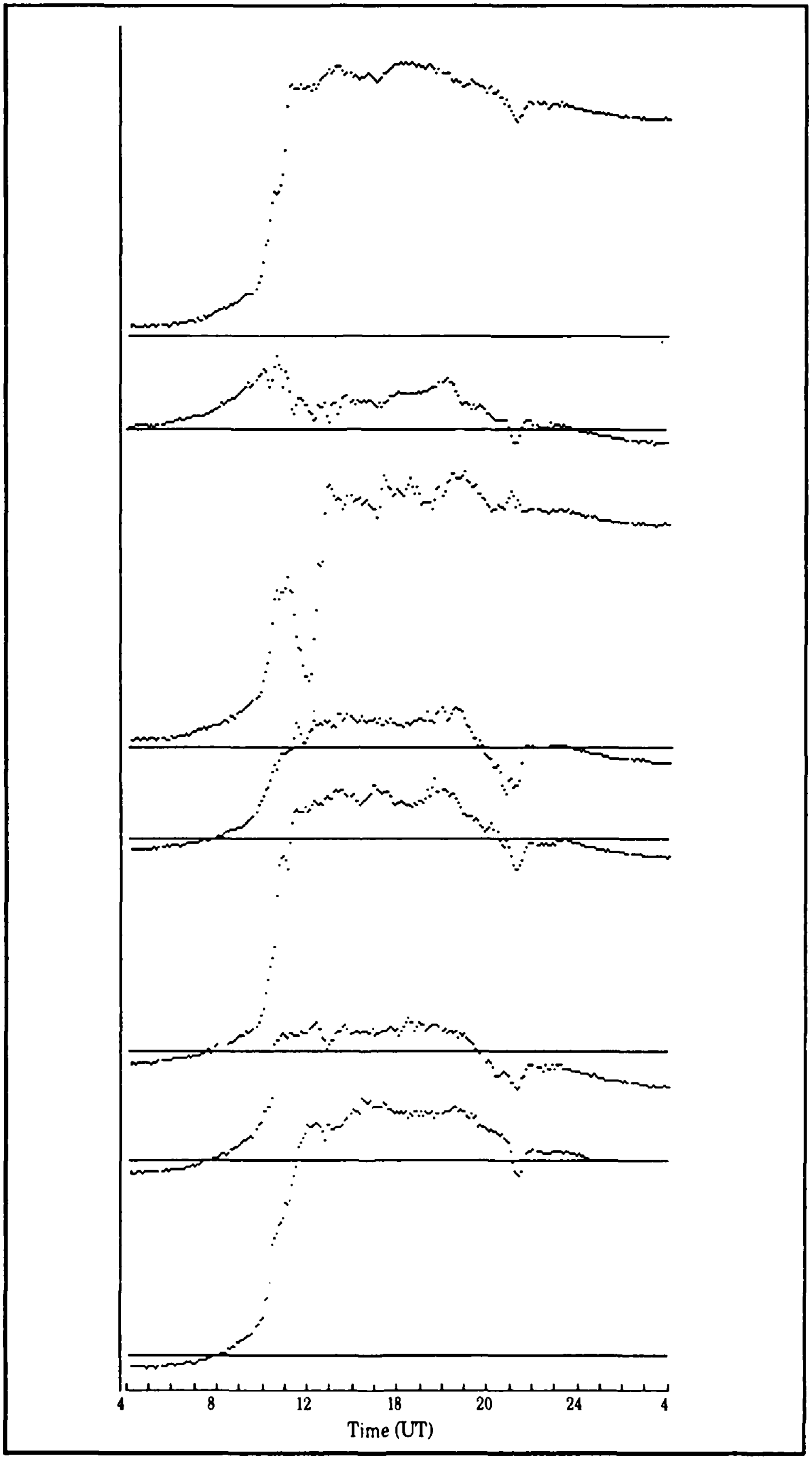

Figure 25. 11.3 kHz Phase, Australia at Cubi Point 01–07 January 1987

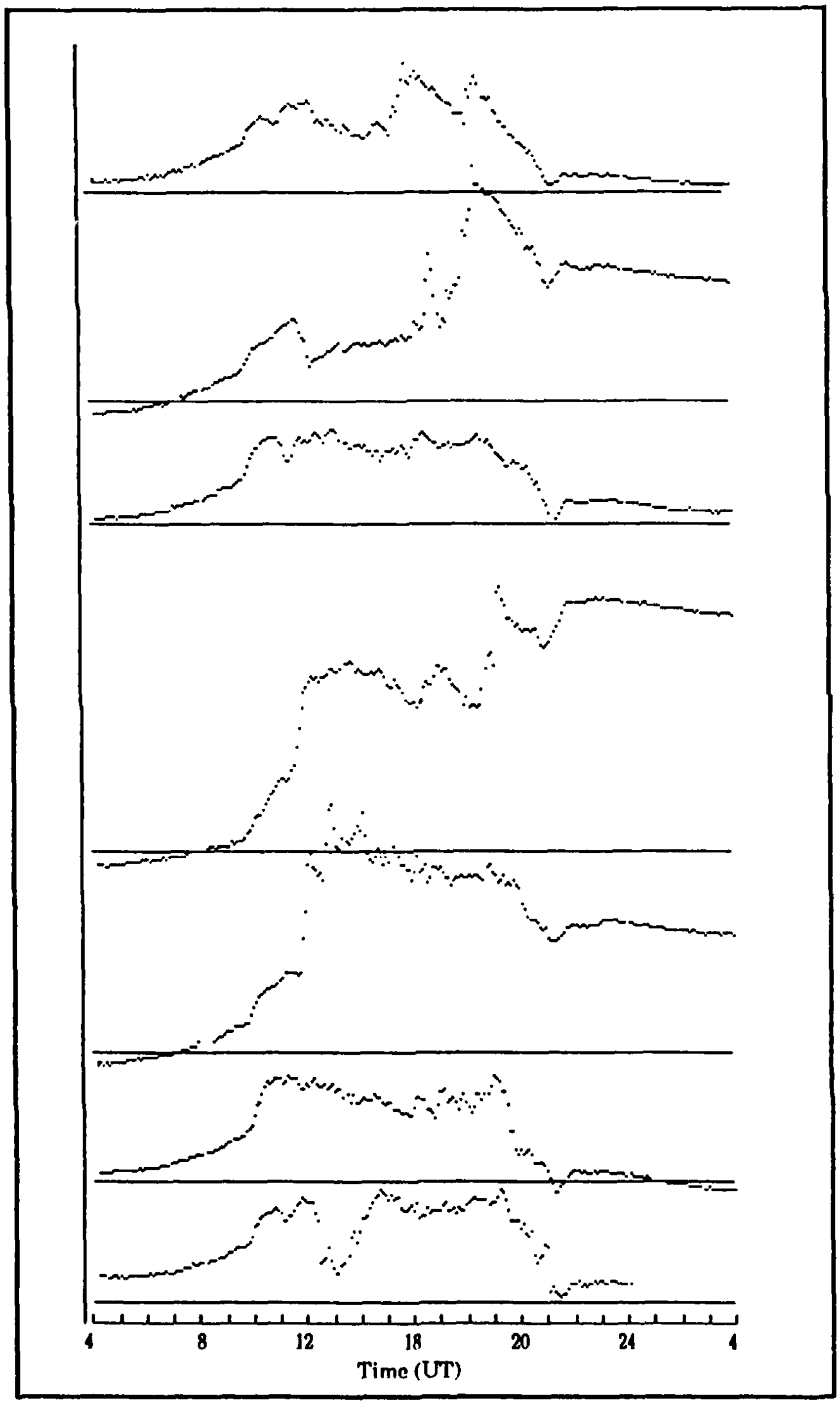

Figure 26. 13.6 kHz Phase, Australia at Cubi Point 01–07 January 1987

other two frequencies and reaches this break in rapid change at the time the 10.2 kHz phase begins its advance. The 13.6 kHz phase shows an indication of following the 11.3 kHz phase but does not follow through. Later when the 10.2 kHz phase starts the second part of its advance, the 13.6 kHz phase makes an abrupt move.

The purpose of this description is to show the interrelationships that can be derived from the data. The ability to interpret the modal content of signals improves rapidly with added information. Thus we emphasize the importance of using all possible, or at least practical, information.

Japan at Cubi Point is at the close edge of its modal conversion zone. We did not know what modal conditions to expect. The 01 to 08 January data is shown in Figure 27. Modal effects are clearly evident. Because of this shorter path, the normal diurnal phase change is less than the examples we have shown before. Note that much variation exists in indicated modal conditions between days. The nights of 02–03 and 03–04 January indicate pronounced modal effects. The nights of 04–05 and 05–06 January indicate intermediate effects and the nights of 06–07 and 07–08 indicate minor effects. A different set of data evidences very different characteristics, as shown in Figure 28. In this record set the first two days show pronounced perturbations with onset in the middle of the night. This middle-of-the-night perturbation onset appears to occur frequently and will be commented on later. In any event, we conclude that there is plenty of opportunity to study the ionosphere characteristics using mode conversion effects.

3.1.4 EXPERIMENT DESIGN

Given that modal conversion occurs and can be measured, the next problem is to determine a good measurement configuration for determining modal composition. We are convinced that a single three-frequency phase measurement is inadequate, in the sense that the model fitting would be unduly difficult. Our concept is to use spaced receivers, each measuring phase and amplitude at four frequencies for each measured Omega signal. The objective is to space the receivers to take advantage of the changing phase relationships with propagation distance between the modal components of the composite signal. The spacing should cover at least one cycle of interference structure, i.e., from a constructive

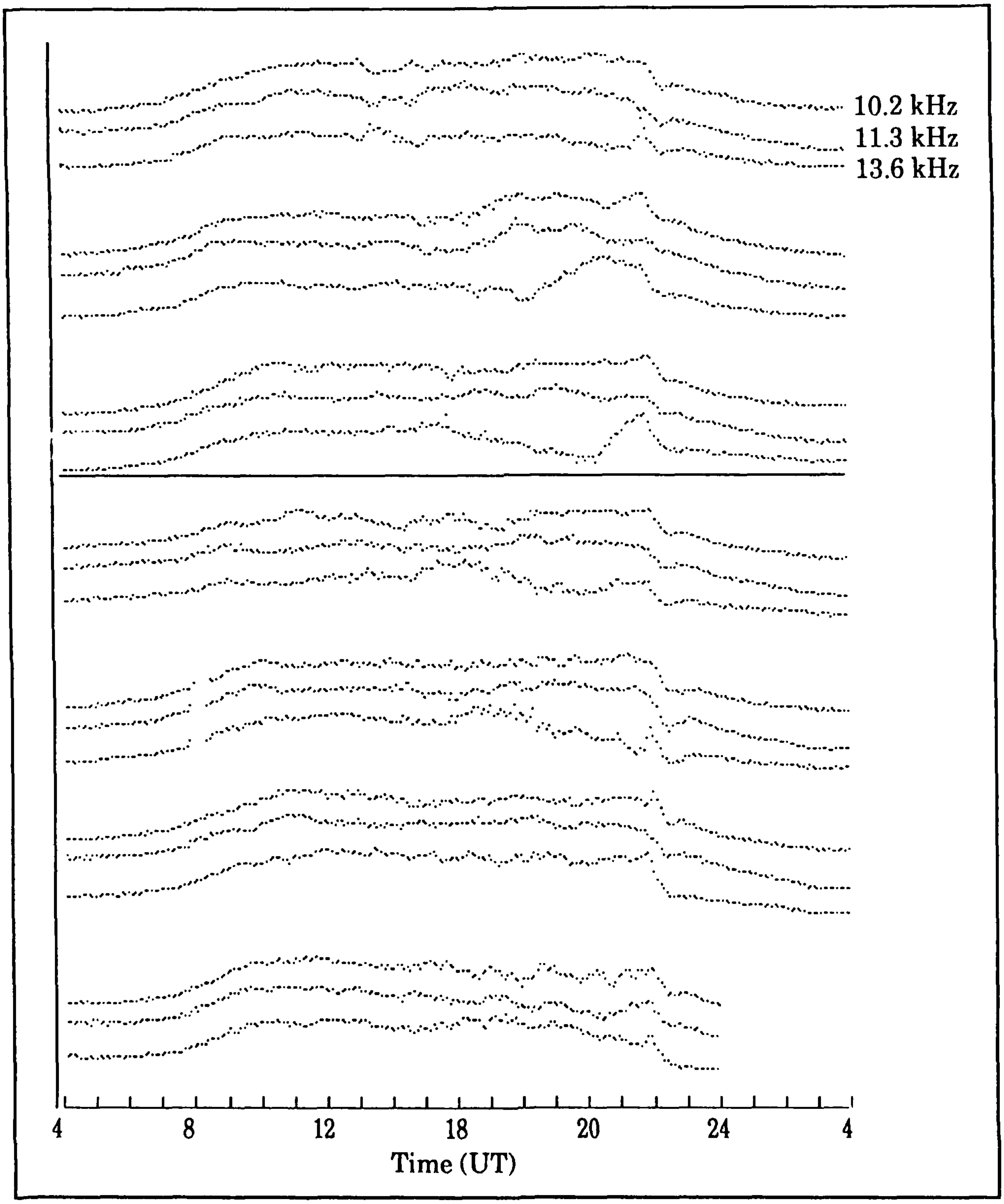

Figure 27. Received Phase, Japan at Cubi Point 01–07 January 1987

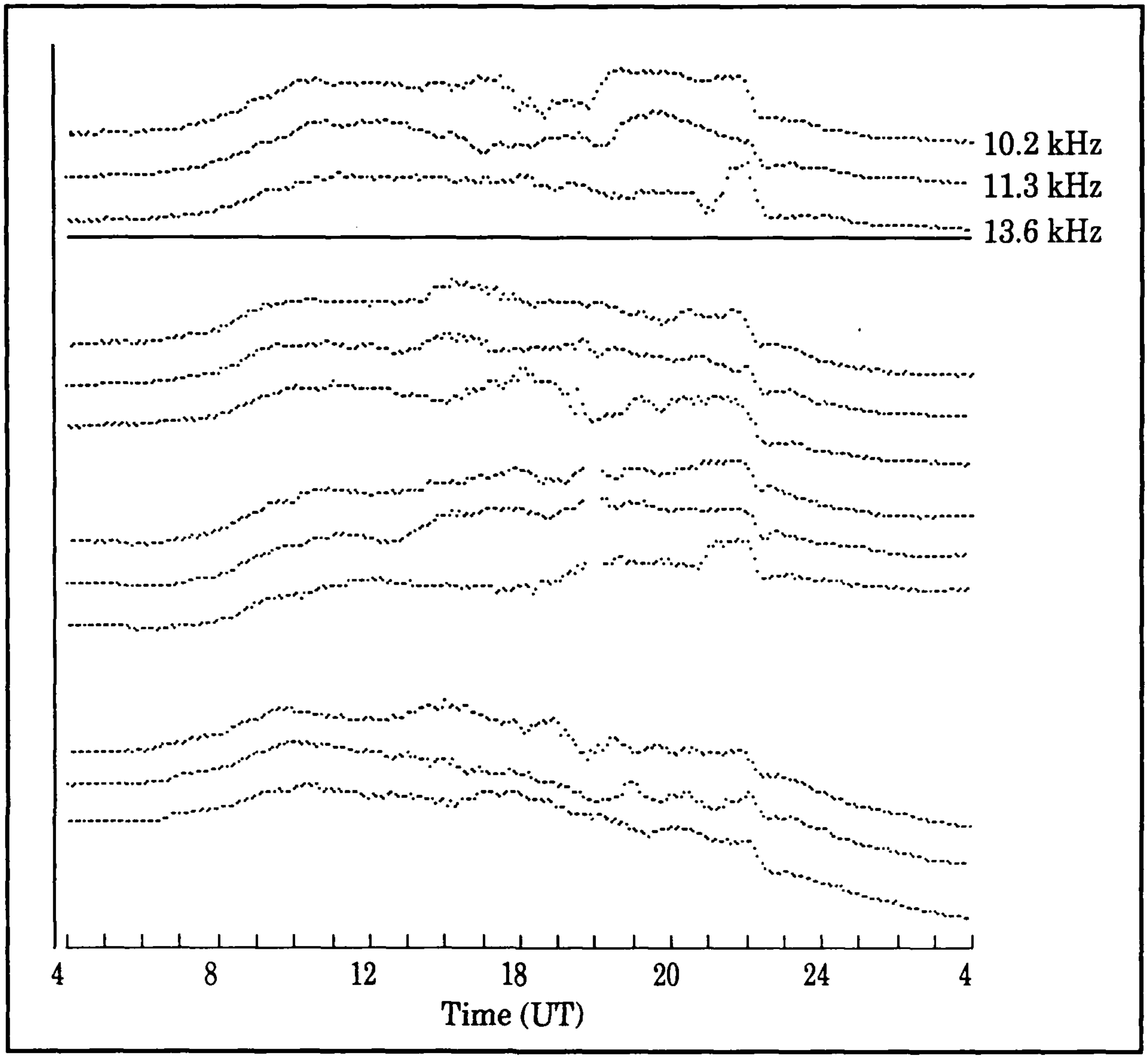

Figure 28. Received Phase, Japan at Cubi Point 19–23 January 1987

maximum through a destructive minimum and back through a maximum. Also, the spacing should facilitate determination of the interference structure across the Omega frequency band. A practical situation would be to locate four sites along a propagation radial over a distance interval corresponding to this composite signal interference cycle. We have examined several sets of flight data to determine the period of the interference structure. We estimate that a representative period is about one megameter, although the typical spacing is still an open question. We feel that the distance interval is not particularly critical nor must the spacing be uniform. Modeling of candidate spacings will help determine

the best choice, but data will provide the best guidance. In practice, site availability will be a big factor in determining spacings.

We have successfully used the technique of deriving ionization profiles from a combination of multiple frequencies, spaced receivers and a theoretical model to infer ionosphere parameters from the propagation data [HILDEBRAND, Ref. 17]. An example of Multi-Frequency Sounder data, from Reference 17, acquired on a propagation path from Hawaii to southern California, with receiving sites at Vandenberg Air Force Base and Lucerne Valley is shown in Figures 29 through 32 for two dates, 28 July and 1 August 1967 respectively. The amplitude data, Figures 29 and 30, is presented to show the patterns produced between frequencies and locations and between days. The phase data, Figures 31 and 32, is for a smaller time interval that covers the 1 August deep amplitude fade on 28.1250 kHz between 1000 and 1100 UT. Our intention was to create a series of ionosphere profiles for the propagation path that would model the propagation conditions that produced the received signals across the period of this fade. An expanded view of the signal fade is shown in Figure 33. To us, the impressive part of this record is that a 40 dB fade occurs at 28.125 kHz, while on the adjacent sounder channels amplitude is essentially level. The deep fade coincides with a marked phase change (see Figure 32) that is noted by the break in the 28.125 kHz curve at 1030 UT. The break is in time coincidence with the maximum signal fade. We were able to account for the propagation changes through this time interval by invoking a set of ionosphere profiles in which the reflection height changed from approximately 81 Km to slightly more than 83 Km. At the same time the gradient of the profile increased slightly. While the fit to data obtained was an achievement at the time, we believe a better fit could have been obtained if the profile had been varied along the propagation path. At that time, we did not have this calculation capability. The data for 01 August, reflected unusually stable conditions over the entire propagation path and we were able to derive an excellent fit using the profiles shown in Figure 34. The match between measured amplitude values and calculations is shown in Figure 35. From the Multi-Frequency Sounder research, we gained an appreciation for the value of using multiple frequencies and locations for obtaining definitive data. We also experienced the frustrations of not having adequate computer processing capabilities.

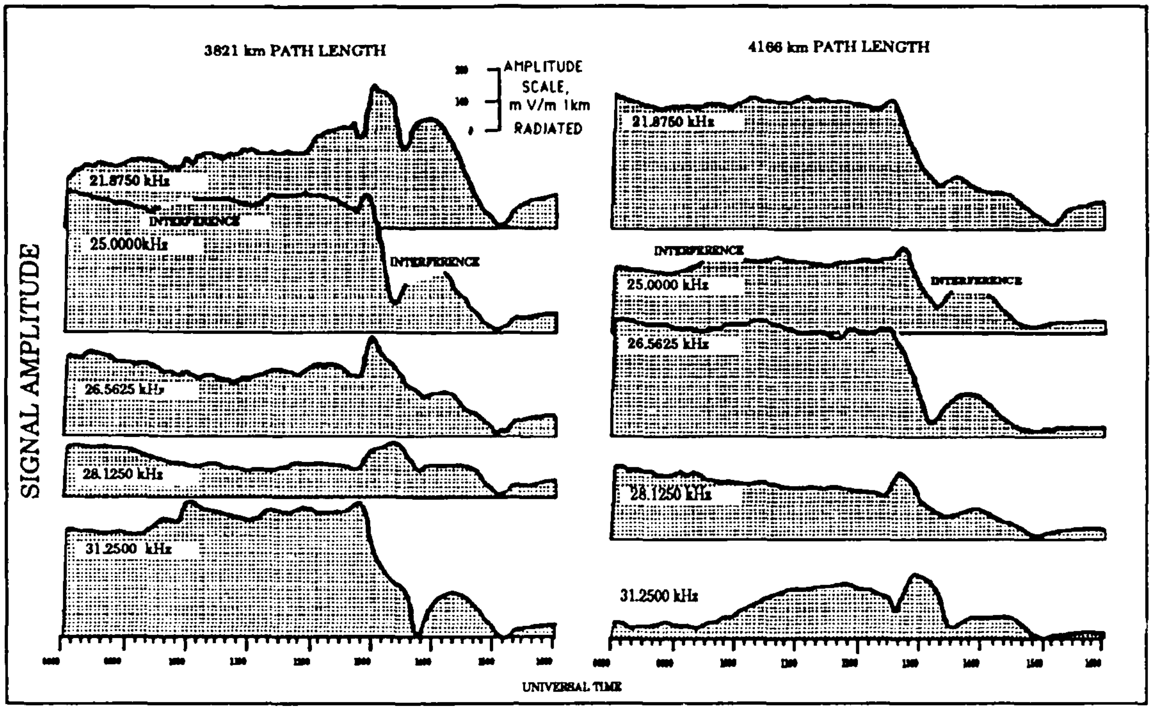

Figure 29. Signals Received at Two Locations on 28 July 1967

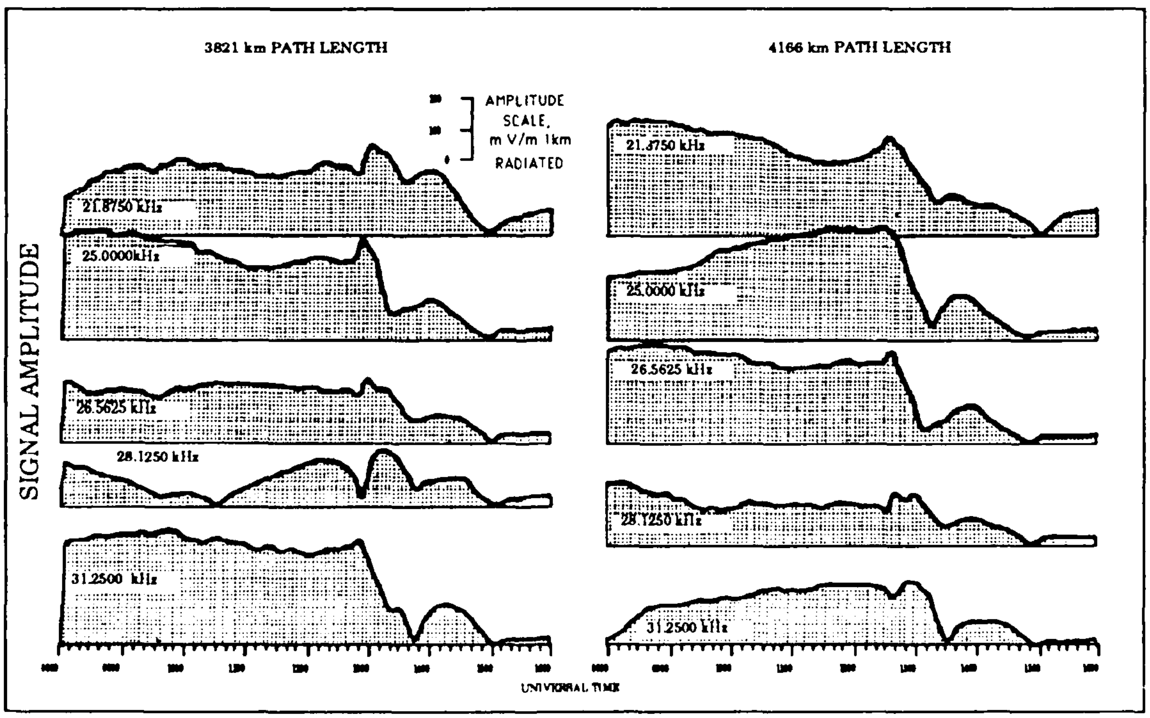

Figure 30. Signals Received at Two Locations on 1 August 1967

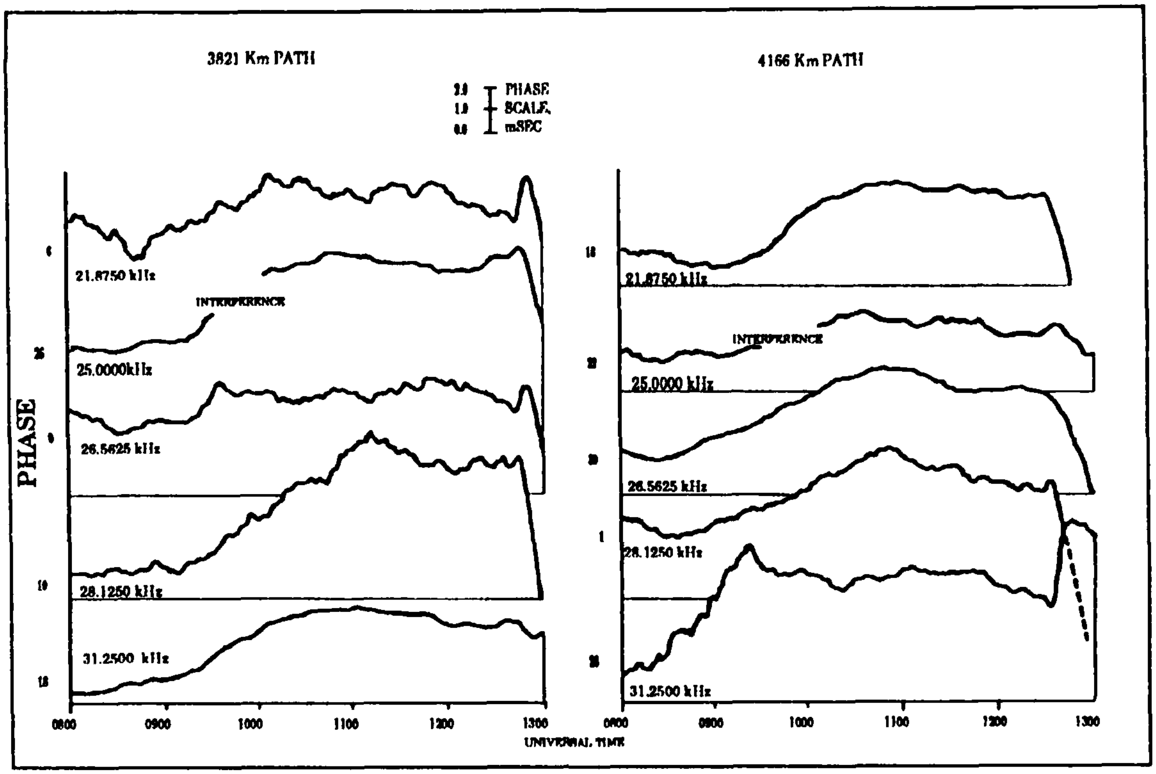

Figure 31. Received VLF Phase for 28 July 1967.

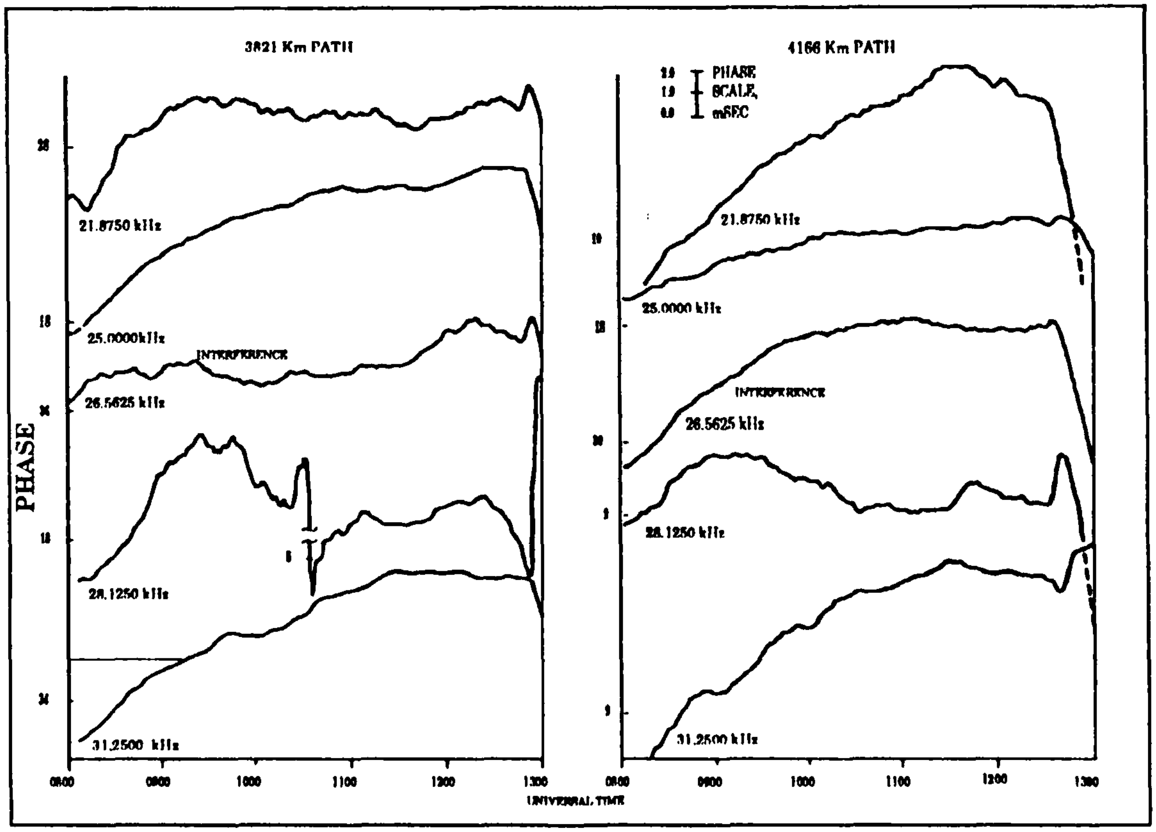

Figure 32. Received VLF Phase for 1 August 1967

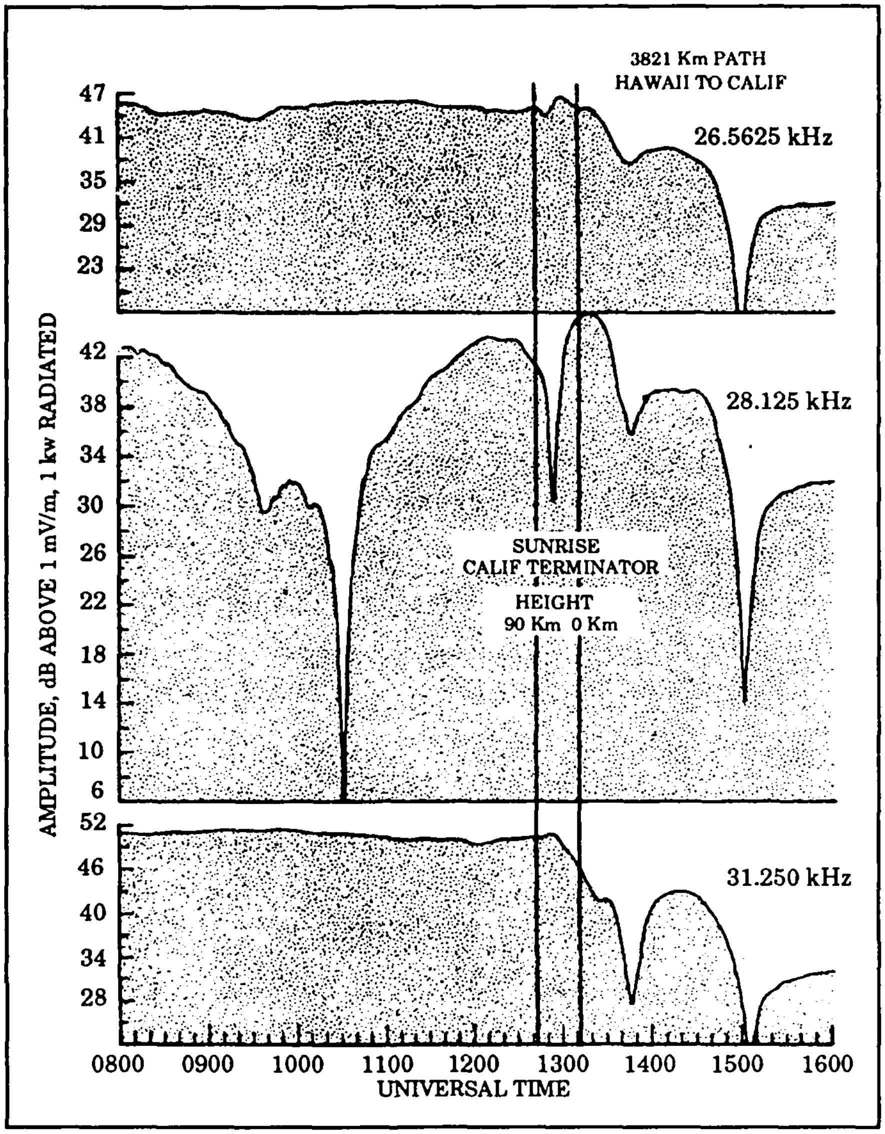

Figure 33. Signal Fade Observed on 1 August 1967

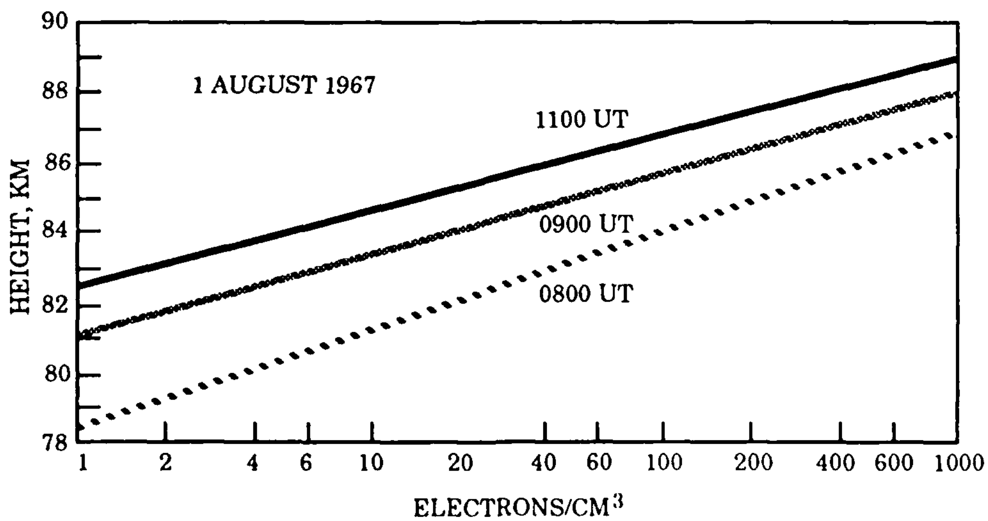

Figure 34. Nighttime Electron-Density Profiles

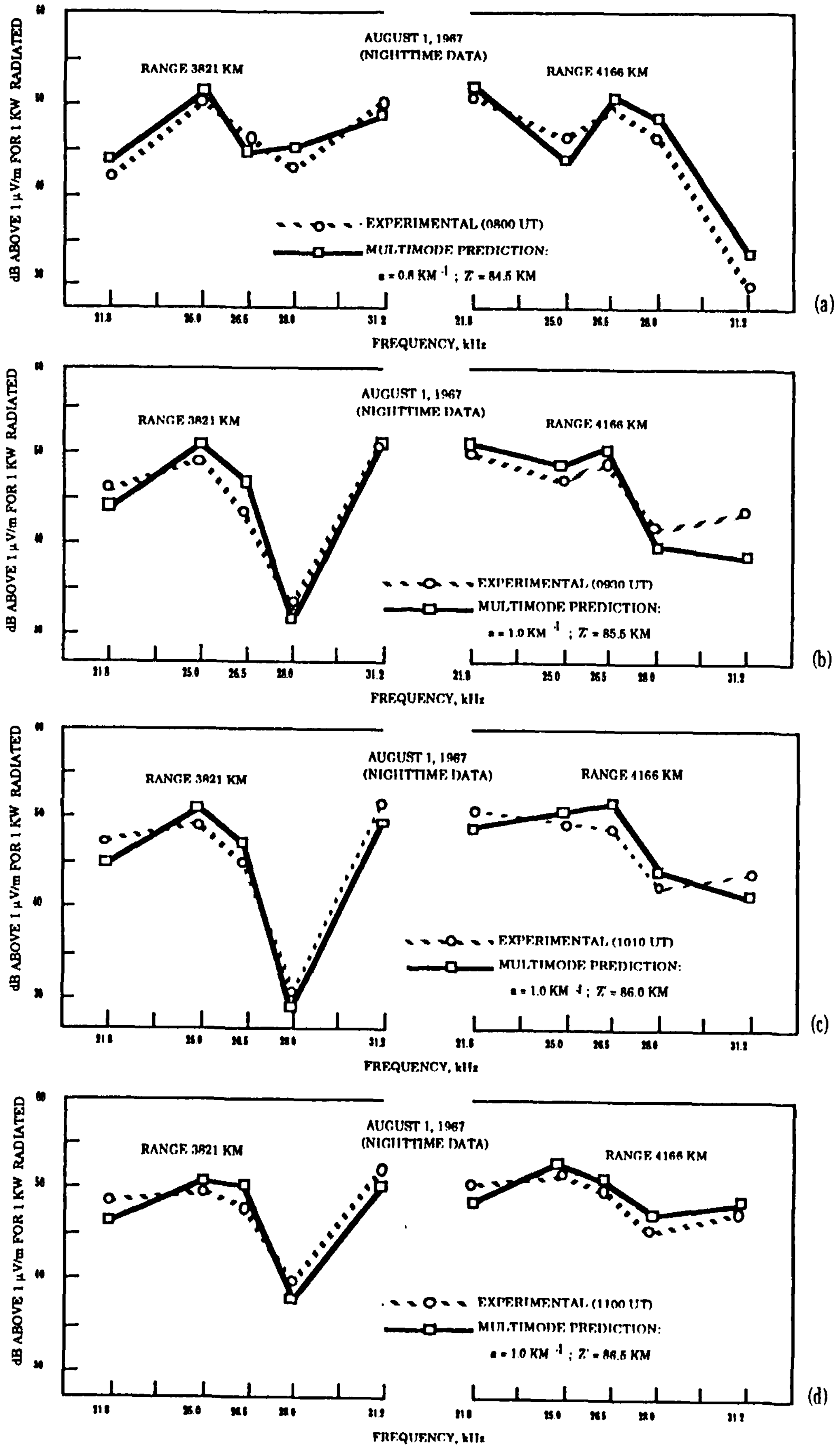

Figure 35. Comparison of Predicted and Experimental Nighttime Field Strengths. (a) 0800 UT, (b) 0930 UT, (c) 1010 UT, (d) 1100 UT

The data of Figures 1 and 2 also provide a good indication of the ionosphere dynamics occurring on the propagation path. This is seen by comparing the 15.6250 and 17.1875 kHz phase and amplitude records for the two nights, 7 and 14 March. After 0800 UT on 14 March the sense of phase and amplitude change for the two frequencies is opposite. This change is consistent with a gradual increase in ionosphere height that did not occur on 7 March.

To summarize our experimental concept, the details of modal effects patterns are expected to be very sensitive to ionosphere parameters within the equatorial zone. The propagation path leading to the interacting zone is not expected to strongly influence this pattern of modal interaction. This is because most of the energy for higher-ordered modes has to come from the dominant mode and the transfer takes place within the conversion region. The relative values of the composite signal that are established by the nearby ionosphere are measured. Thus the measurements sense a localized area, a few megameters, depending on the placement of receivers with respect to the mode conversion onset location. With placement of receivers along a path, an interferometer effect is obtained that enhances the measurement of modal effects and thus information content about ionosphere structure. The findings of the Phase One investigation have strengthened this concept and provided sufficient details for experiment design. We are now quite sure that mode conversion does occur, that this occurrence is confined to a limited portion of the propagation path, and that the conversion process is very dynamic in time. The Phase One analysis has made it possible to define a geographic area for the experiment and has provided guidance for selecting measurement configurations. The experiment design will be completed after conducting computer simulations of modal conversion effects and after exploring measurement site options with cognizant personnel in the region of interest.

4.0 MEASUREMENT INSTRUMENTATION CONSIDERATIONS

As stated in the introduction, gathering knowledge on the properties of the lowest D-region ionosphere has historically been a particularly difficult challenge. All measurement techniques have major limitations, due to such factors as sensitivity and accuracy, reliable interpretation, practicality of implementation and cost. As both users and producers of D-region data, we are well aware of the dif-

ficulties. As specialists in VLF radiowave propagation, we are also somewhat aware of our biases. Ideally, a cost-benefit study should be made of candidate measuring techniques. Such a study is premature. We have ruled out many techniques for lack of expertise. We have, however, considered various methods for studying the lowest ionosphere dynamics so as to be aware of research findings, to establish contacts, and to instigate cooperative efforts, should the opportunity arise.

4.1 EXPERIMENT SITE SELECTION REVIEW

Much of today's ionospheric research is being conducted at large dedicated installations, none of which are located close to our candidate experiment area. Some D-region research is being conducted, but generally at higher levels than that observable with VLF. We considered conducting our measurements at or near one of the existing facilities. Principal equatorial research facilities or campaign areas that we considered were; Hauncayo in Peru, Kwajalein Island, Arecibo in Puerto Rico, Natal in Brazil, southern India, and western Africa. To coordinate with other research at a facility, we would have to pick a measuring location that places the last VLF reflection over the facility.

Some of the considerations involved can be illustrated using Hauncayo as an example. Candidate signals are from Norway, Liberia, La Reunion and Argentina. For the Norway signal the receiving site would have to be 1300 Km along the propagation path south south-west. San Felix Island is close to the needed location. For Liberia, the site would have to be 960 Km into the Pacific Ocean with no islands nearby. For La Reunion, the site would have to be about 1500 Km to the northwest. The Galapagos Islands could be used. For Argentina, the site should be 1350 Km north and west, near Quito, Ecuador. Other considerations are: for Norway, the northern end of the path would not reach full night conditions for part of the year; for La Reunion and Liberia the signals are long-path during the normal day period. Having a clean mode 1 daytime record is considered an important reference for interpreting the day/night transition periods. Also, our South Pacific Validation data at Arequipa, Peru shows that the long-path interference for these two signals extends well into the day/night transition period. We conclude that the propagation situation is too complex for initial ex-

periments. The Norway signal was weak at Arequipa, probably due to the intense thunderstorm activity in the Amazon region. Using the Norway option would not be a good first choice. The Argentina option provides the best choice. The propagation path is all over land, and so the predictions would not be as straightforward as for an all water path. Using the Argentina option, only the Argentina signal would be consistently of good quality. The return on investment, other than coordinating with other research, is clearly very low for locating in the vicinity of Hauncayo. The benefits of coordinating with other experiments can be high and should be carefully considered for future endeavors.

Interestingly, the situation described for Hauncayo is representative of all of the equatorial research facilities we considered. This example is also representative of opportunities associated with any other geographic area we considered, except the area surrounding the South China Sea. Our candidate region provides a much better VLF opportunity. In addition, we have the potential benefit of coordinating with Australian and Japanese VLF propagation researchers.

4.2 VLF RECEIVER PERFORMANCE CONSIDERATIONS

Important receiver features for data collection include high sensitivity, good noise discrimination, frequency stability, low cost, reliability, and ease of use. We have not found an optimum receiver for our needs. Each of these features can be improved upon for our purposes by using the latest technology. We believe that a high quality signal monitoring instrument can be economically assembled and will be cost effective. The general availability of high performance components at very low cost makes it practical to fabricate receivers. Manpower savings during the analysis phase are expected to justify the cost of fabrication.

Our concept of this receiver is shown in block diagram form in Figure 36. Note that the receiver is mostly digital with analog circuitry used only for preamplification and band-pass filtering. Several types of antennas are being considered. A likely choice for high noise sites is a cardioid unit consisting of ferrite loops in a square configuration for the magnetic component and a parallel plate for the electrical component. This antenna unit would be electronically switched by the system control in synchronization with the Omega station transmission

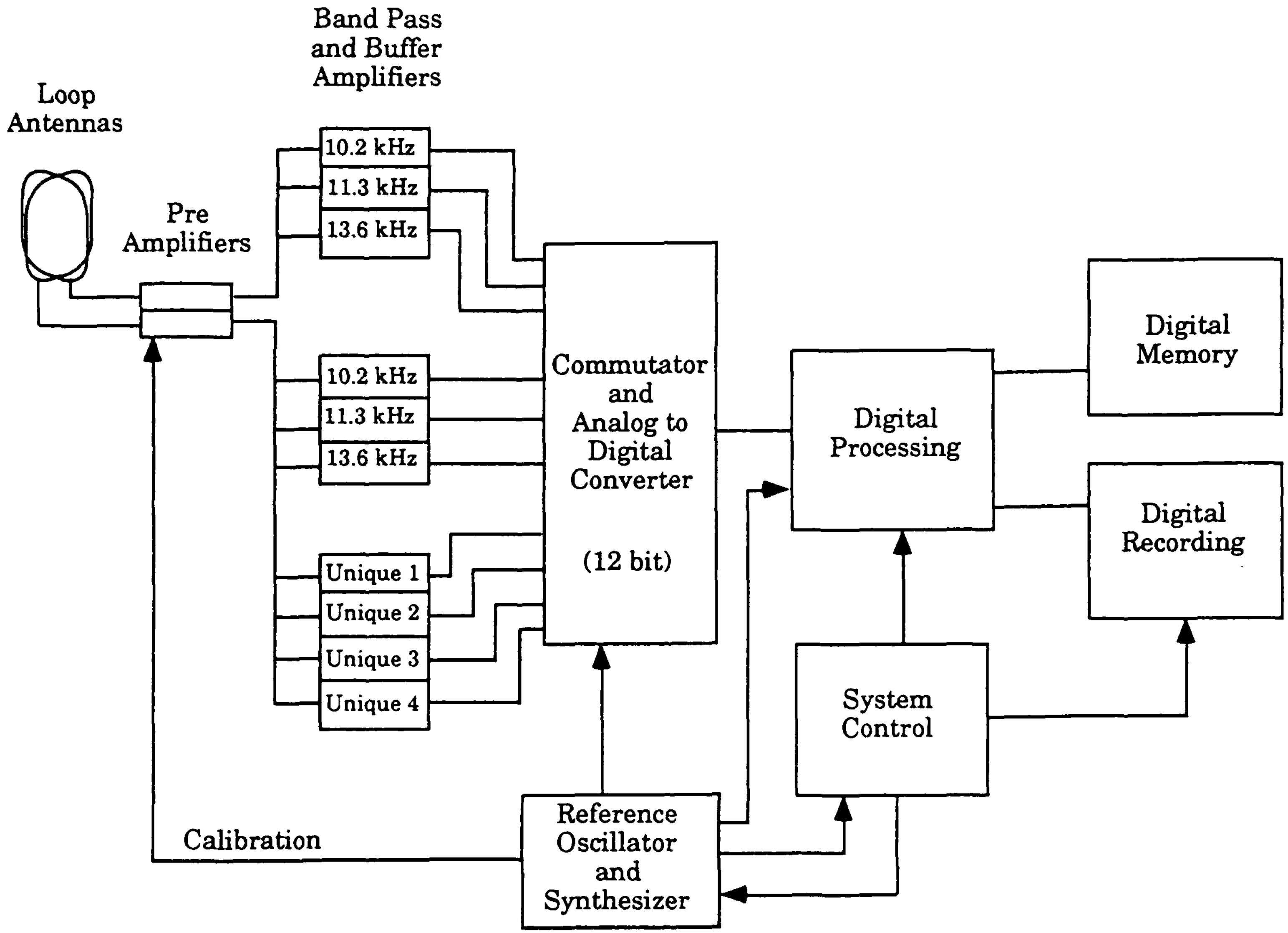

Figure 36. Omega Signal Phase and Amplitude Recorder

sequence. The switching would adjust the cardioid pattern to optimize signal-to-noise for each station. Low noise preamplifiers have been produced by INOTECH, that with a good antenna can provide atmospheric noise limited reception. Nonlinear signal processing would be included prior to the band-pass filtering to pick up an additional 10 to 15 dB sensitivity. The band-pass amplifier gain will be digitally controlled if dynamic range improvement proves to be beneficial. A high speed analog-to-digital converter will sample the radio frequency (RF) waveforms from each band-pass amplifier. The signal sample rate will allow measurement of waveform phase and amplitude. Appropriate digital samples will be integrated by an add-to-memory scheme to build up the signal-to-noise ratio. Large data blocks will be built up in digital memory and at selected intervals transferred to recording media. The digital processing, using a general purpose computer under software control, will allow high flexibility in operations.

Reference oscillator stability is an important consideration. At least two orders improvement in stability are needed over the Omega monitoring receivers used in the Western Pacific Validation Program. After checking prices, we concluded we did not need the accuracy of atomic standards. Mainly we want to track phase over a 24-hour interval. If necessary phase drift can be adjusted by assuming linear drift and that successive values of mid-path noon are the same. We devised this technique for processing the Western Pacific phase data and found we could use most of the data. Higher stability reference oscillators would make this process quite adequate. Our plan is to use a double-oven crystal oscillator and a synthesizer to provide clocking for the entire system. It may be practical to adjust the reference oscillator by computing the daily drift and adjusting the oscillator oven temperature.

With respect to component hardware, all the components needed, except the band-pass filters and antennas, are standard commercial items. We would build the unit around a standard AT computer motherboard. Sixteen megahertz clock-rate motherboards are available wholesale for under two hundred dollars. Twelve- and sixteen-bit analog-to-digital converters are also reasonably priced and compact. The band-pass amplifier units all could be placed on a small printed circuit card. The antenna units already have been prototyped. Personal computer power supplies are also low cost and reliable. Considering the likely humid ocean environment of the monitoring sites, we plan to package the instrument in

a water-tight metal box. All components are readily available, so parts replacement should be easy. Added components will be a keyboard and a monitor. These items may be exposed to corrosion, but could be detached and stored in a protective compartment if not used for long intervals. Both units could be detached while the equipment is operating. Software would be provided to allow data display on the screen. Diagnostics could also be performed by using software. Calibration would automatically be conducted via signal injection at the antennas. We are considering a calibration procedure that would not interfere with data collection.

A detailed receiver design and a prototype model will be created during Phase Two. Our plan is to make these custom receivers the principal units for the research project. As many units as practical will be fielded. The plan is to gain some experience with one or two units, and then add a few more as the design is optimized and software developed. Our desire is to augment this core capability with whatever monitoring equipment can be placed in service. We will be exploring possibilities for utilizing the Coast Guard equipment and for coordinating with other researchers.

4.3 PLANNING FOR EXPERIMENT INTERPRETATION

The modal structure for any ionosphere condition will have a distinct pattern with frequency and distance. This characteristic is much the same as observed with the Multi-Frequency VLF Sounder developed by the principal investigator under previous ONR support. Examples of sounder data and our interpretive experience have been described in this report. We plan to employ almost the same experimental technique used successfully with the sounder, that is, to use several strategically placed measurement sites and to measure as many frequencies as possible at each site. Interpretation of such data is quite challenging and requires the use of propagation calculations iteratively with measurements. The technique is essentially a pattern fit of calculated to measured phase and amplitude with frequency and position. The calculations are successively run from clues derived in previous attempts until an adequate fit is obtained. We found with the sounder, that in a dynamic situation, iteratively fitting calculated signals with measurements over a time period proved more fruitful than attempts

at static fits. With the VLF sounder we were able to trace ionosphere height changes over several hours, locating the "reflection height" at each selected time to 0.1 Km. Interpretation of VLF sounder data required a significant learning curve. A significant learning curve will also be required for this project. However, we also have a great deal more experience to build on. An equally important factor is, that with the VLF sounder analysis, very little computer time could be afforded and elapsed time between calculations was long. Today a desktop workstation has the power of mainframes used in 1970 and results can be obtained in minutes rather than overnight.

During Phase One, we have been exploring computational techniques on a prototype of the workstation we plan to use for data processing and analysis. Though this exploration is still continuing, we have focused on two theoretical methods for electron density profile derivation. Since we are dealing with ionosphere variation along the propagation path, the computer codes required will have to be quite sophisticated. The primary effort will be pursued using the NOSC full-wave VLF propagation prediction codes. We now have these codes transported to our workstation and running. We are in the process of creating an executive driver that will minimize the manpower required to set up an analysis. Again, we have the benefit of code developed by NOSC to use as guidance. Since these executive codes are very machine dependent, this adaptation will take more effort than adapting the waveguide codes. These codes, as used by NOSC, generate composite field display products. We need output of the individual modes, so some additional minor adaptation will be required.

These NOSC full-wave codes will be used because they are known to be robust, and extensive calculations are available for benchmarking. From our perspective, the Wavehop concept originally developed by Berry [Ref. 18] is more ideal because of the correspondence to physical aspects of reflection zones. Berry's technique has recently been extended by Frank Kelly of Naval Research Laboratories (NRL), [private communication] to allow ionosphere variation along the propagation path, a feature not included in the original development. We intend to explore the feasibility of adapting his codes for our analysis.

Dynamic interactive analysis is a critically important capability for achieving the analysis goals of this project. Correspondingly, we are configuring a personal

workstation computer that will support real-time computational products on large screen graphical displays. Our goal is to achieve the ability to obtain immediate calculational results that fully support the thinking processes. Our plan is to have this capability fully operational during Phase Two of this project. This workstation will provide at least 17 times the capacity of the benchmark VAX-11 780 in a desktop unit.

5.0 EVIDENCE FOR IONOSPHERE PHENOMENA OF INTEREST FOR STUDY

Our research goals are to contribute to the overall understanding of geophysics systems. Our plan is to utilize the broad knowledge base of ionosphere, meteorological and solar-terrestrial physics along with VLF propagation experiments to achieve a better understanding of equatorial D-region ionosphere phenomena. Our premise is there is a dearth of knowledge about the D-region, especially as regards the coupling of meteorological phenomena to the E-region and F-region ionosphere. In this investigation we focus on the the more specific problem of studying the D-region ionosphere. Our effort follows two avenues: (1) further examination of the literature and (2) a search for experimental evidence of equatorial dynamic effects.

5.1 LITERATURE REVIEW

We conducted a literature review of research relevant to our investigation. Specifically, we looked for descriptions of phenomena that might be detectable with our proposed measurements and for models that might aid interpretation of our data. Our interests were broad: the D-region ionosphere is part of a complex dynamic global system that involves the atmosphere and the magnetosphere in various intrinsic coupling networks. In recent years, perspectives on ionosphere plasma processes have expanded from narrow views on local phenomena to more global approaches that recognize the importance of many coupling mechanisms. Major cooperative multidisciplinary projects have been undertaken to investigate such diverse phenomena as equatorial spread-F and high latitude responses to substorm activity. This broad view recognizes and even emphasizes

that the various ionosphere domains are both active and interactive elements in the much larger solar-terrestrial network. Numerous review papers, of particular value to us, have focused on developing an understanding of dynamic and irregular ionosphere structures and their relationships to local and remote geophysical controls [cf. CHIU et al., 1984; WOLF et al., 1982; FISK et al., 1984; SZUSZCZEWICZ, 1986; Ref. 19–22].

Probably because of the dearth of material covering the D-region, the nighttime F-region has continued to exert a strong fascination. Certainly the equatorial F-region has received the more intensive investigation and thus is better understood in relation to some of the complex phenomena [ABDU et al., 1983; KELLY et al., 1986; Ref 23 and 24]. Just the magnitude and complex interaction of F-region structures spanning six orders of magnitude from fractions of a meter to hundreds of kilometers, suggests that the D-region must be susceptible to F-region dynamics. We know that large current systems and weather patterns with effects originating in one region couple to phenomena in other regions. Equatorial Spread-F (ESF) is characteristic of the large dynamics of special interest to us. Spread-F is a disturbed nighttime condition that is characterized by large scale plasma "bite-outs." Bite-outs are complicated ionosphere holes that can extend 100 Km in width and have ionization depletions 1–2 orders of magnitude. The equatorial spread-F process is a nighttime phenomenon, occurring at approximately 2300 LT ±3 hours, centered about the geomagnetic equator, ±20° latitude. Seasonal, solar-cycle and day-to-day variations of spread-F occur. The reason for our strong interest in spread-F for our planned research is that much evidence exists to indicate that the driving force creating spread-F and related disturbances originates below the F-region, possibly within the atmosphere. Argo, in analysis of digital ionosound observations at Huancayo in Peru, suggests seeding of F-region disturbances by gravity waves of nearly local origin, possibly from the rain forests to the east or from the Andes mountains. If this is so, the D-region must also undergo disturbances.

It is appropriate to reemphasize that the lower ionosphere, D and E-regions, in contrast with the F-region, are far less understood, particularly in terms of large scale dynamics and irregularities [SZUSZCZEWICZ et al., 1978; FEJER et al., 1980; PFAFF et al., 1984; Ref. 25–27]. The main reason is that these regions are not accessible to satellites for systematic global investigations. These regions must be

probed with rockets, ground-based radar high frequency (HF) sounding systems, and various optical means. These methods lend to geographic-localized measurements which by their very nature create little information on large-scale horizontal variations. It should be understood that these regions can contribute to an interactive exchange with a number of F-region irregularity processes. The lower ionosphere must be reckoned with, in attempting to model the total solar-terrestrial processes. As an example, the E-region irregularities, sporadic-E, auroral-E, and equatorial electrojet each have a larger geomagnetic distribution than the corresponding F-region irregularity.

Our early rationale for conducting D-region research is still considered valid: for equatorial D-region research, several correlative possibilities are worth investigating. First, much evidence is being gathered that the seeding source for spread-F originates below the ionosphere and thus must travel through the D-region. Gravity waves, which are a possible source, are detectable in D-region VLF reflection patterns and thus should be explored. Useful models exist for explaining gravity wave propagation from surface sources to ionosphere heights. Second, while much attention has been given to F-region phenomena to explain the observed mechanisms, much evidence exists to suggest strong coupling to lower layers. As an example, much of the occurrence cannot be well correlated with ionosphere geophysical dependencies on solar effects or seasonal variability. Attention should be directed to meteorological influences, many of which, if coupled to the F-region, should be observable in the D-region. Third, spread-F always initially occurs at the bottom of the measurable ionosphere (with the techniques used) and when the ionosphere is high (that is there is deficient ionization at lower elevations). Such high ionosphere heights are associated with electric fields and other phenomena that should affect other regions. Anomalous variations in reflection height are also observed in the D-region. The possibility for coupling of height variations between layers is worth investigating, as is the explanation for their occurrence. Is their occurrence due to electrical currents, such as the E-region equatorial electrojet, or to meteorology such as weather patterns? Fourth, strong irregularities observed at the bottom of the ionosphere will probably extend even lower than present sensors record. Testing this possibility would produce much material for theoretical modeling.

5.2 EXPERIENCE WITH DATA INTERPRETATION

During this feasibility analysis, our opportunities for assessment of data that gives clues to equatorial D-region dynamics have been quite limited. Much of the data that we had hoped to examine requires much more processing work than we had anticipated. The processing methods are being refined but much time has elapsed. The major processing problems have been reference oscillator drifting and frequent breaks in the data sequence, often with resulting phase offsets and different phase drift rates. Much of the data we have examined is for propagation paths outside of the modal conversion zones. Gaining analysis experience with this data is beneficial in that the interpretation is less difficult. However, less information is also obtainable for deriving ionosphere parameters. We have found a variety of propagation effects. Particularly notable effects are (1) times when the entire nighttime period evidences anomalous propagation and (2) times when a distinct onset of anomalous conditions is noted. One condition noted several times is shown by the examples of Figure 37. Here the phase height increases markedly soon after midpath midnight and remains high until the sunrise transition. This is definitely single-mode propagation, in that the phase records from the three recorded frequencies track very closely. These phase records show a phase shift that is about a 30 percent increase over the typical day-to-night height change. If the reflection height were uniformly increased this phase change would represent about a 6 Km h ht increase. Since this path is dominantly 3 hops, the greatest reflection height change that could occur would be at one reflection region. Thus the height change would be or 3 times the average or 18 Km. Since the reflecting regions cannot be isolated, no further information is available on the geographic extent of the ionosphere rise. The mode conversion measurements should help resolve some of this uncertainty, especially since several of the paths are dominated by a two-hop geometry.

The onset of a propagation perturbation following midpath midnight has been observed several times in the data we have examined for this study. A comment was made earlier about the modal effects of such a perturbation in describing the Australia phase data recorded at Cubi Point. The time of occurrence matches well with the reported typical onset of Equatorial Spread-F (ESF). We noted in our literature review that ESF is a nighttime phenomenon occuring within ±20

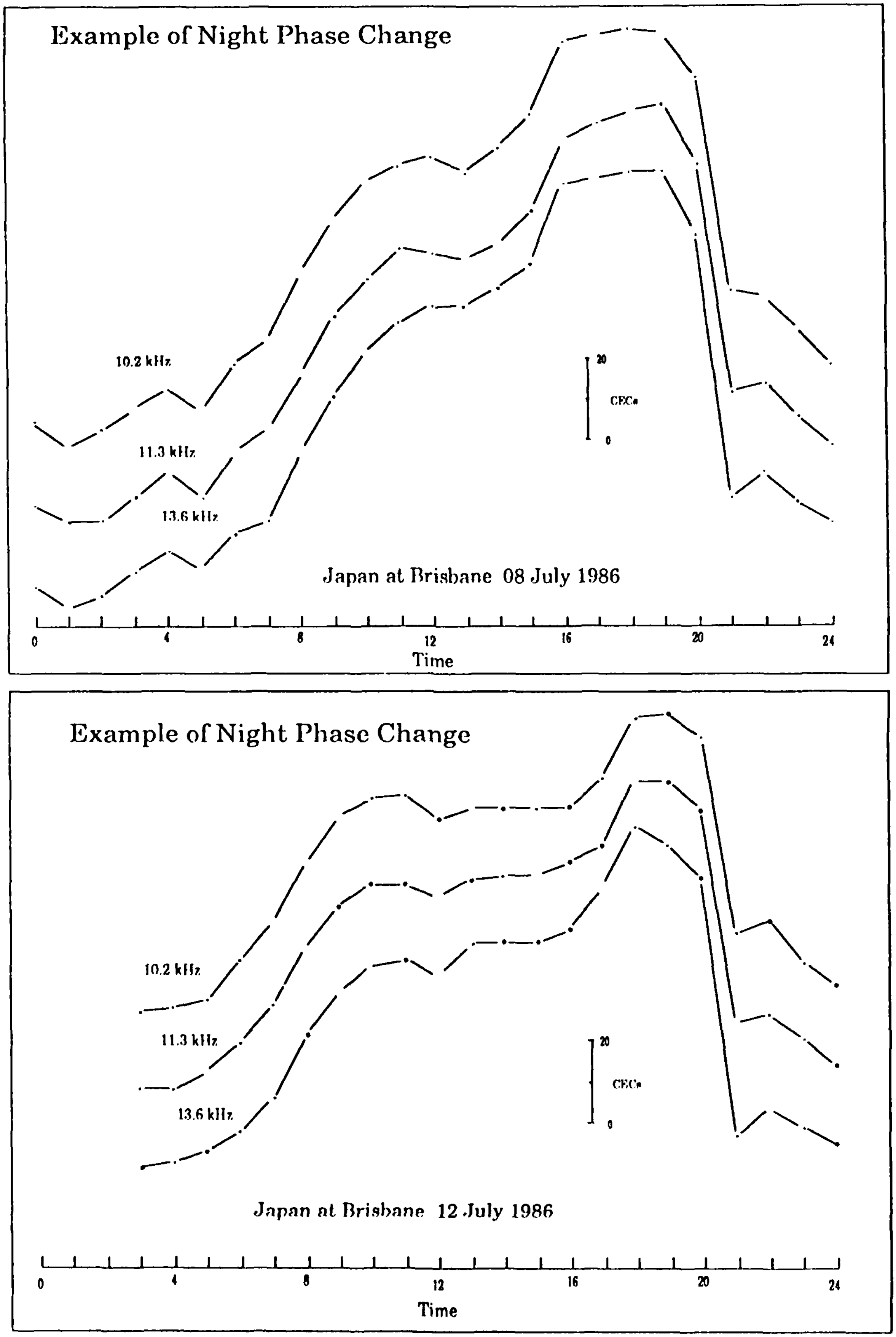

Figure 37. Nighttime Phase Perturbation Effects

degrees of the equator.

Another important objective is to derive information on the ionosphere structure within the mode conversion region. Presently almost all VLF propagation modeling is done using exponential electron density profiles to represent the ionosphere D-region. We expect that these profiles are unrealistic, but better representations have not been derived. For long-path propagation prediction the exponential profile may be a good choice. For aeronomy studies more structural detail is desired. Any guidance that can be derived for structure selection is valuable. Recently John Rasmussen of the U. S. Air Force Geophysics Laboratory provided a report describing VLF sounder experiments conducted in Brazil near 26°S latitude [KLEMETTI, Ref. 28]. This report shows evidence of the VLF wave penetrating the nighttime D-region and reflecting from downward traveling disturbances as high as 174 Km. This data, shown in Figure 38, strongly indicates that the VLF is capable of interacting with a large portion of the nighttime D-region. Since the sounder uses a short-pulse transmission, we are not sure how much of the lower frequency component penetrates through the lower reflecting layer. We hope to study this data more closely. What is needed is better resolution in time and frequency spectrum analysis of the data.

The VLF short-pulse sounding research conducted by the Air Force Geophysics Laboratory has consistently showed the value of pulse waveform measurements for revealing ionosphere VLF reflection properties. The above report shows several features that would be difficult to observe by other methods. Their work has led us to reexamine a short pulse sounding technique developed in the early 1970's by Wieder and Espeland [Wieder, Ref. 30]. Their sounder used the 100 kHz Loran C transmitters. Our primary interest in this technique is to obtain the spatial resolution in ionosphere reflection that cannot be obtained with the long Omega pulse. The very complex receiver fabricated by Wieder could easily be incorporated in the same personal computer-oriented receiver we plan to fabricate for our measurements. With modern digital signal processing chips commonly available on plug-in boards, building a Loran C sounder receiver would be simple. A major problem is experiment location. We understand that all of the Loran transmitters in or near the Western Pacific, except for Guam, have been shut down. This technique is very interesting to us and we will continue to explore the potential of this concept.

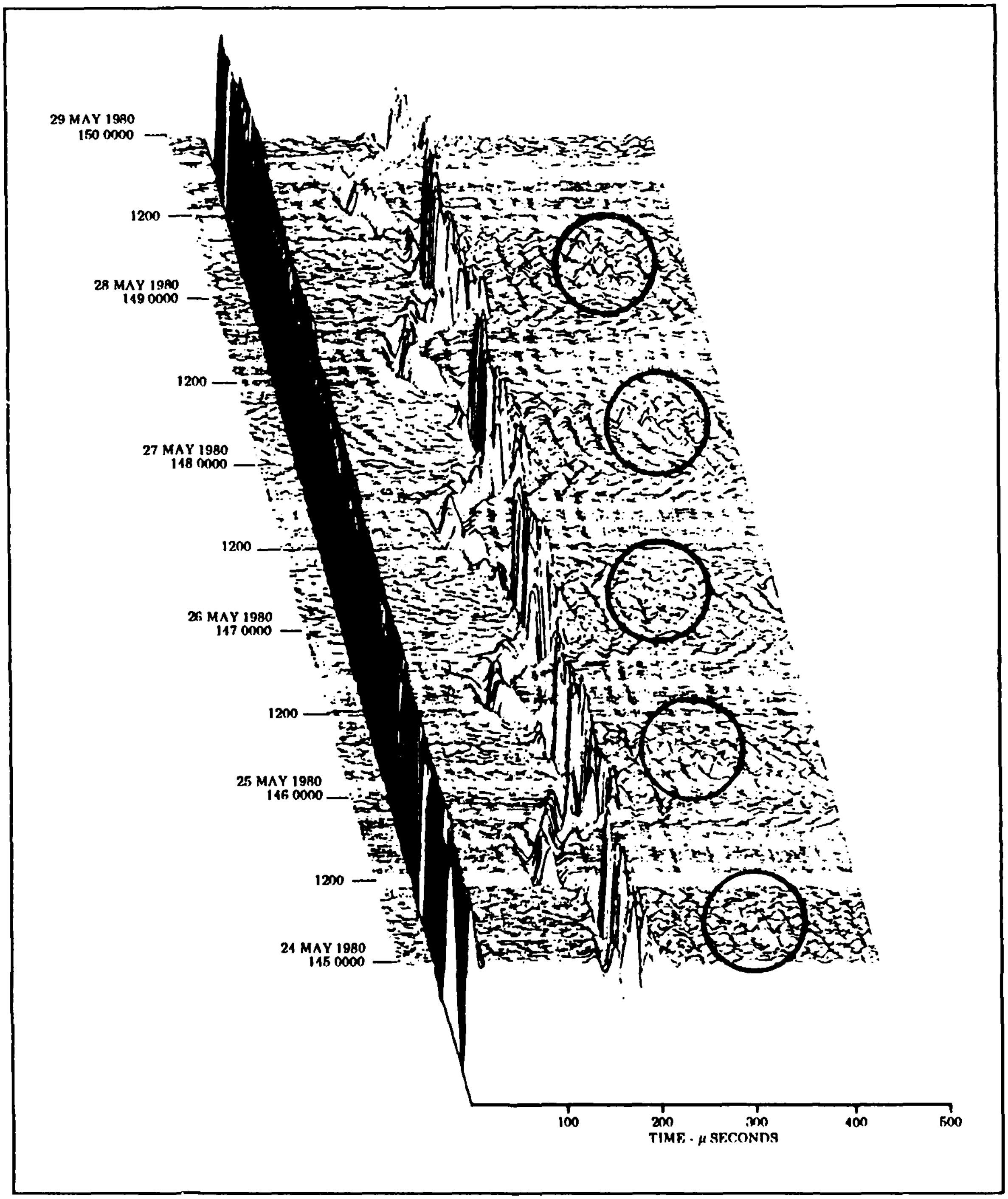

Figure 38. Moving Reflections Above D-Region

6.0 A RESEARCH ACTIVITY PLAN

In this section we will present our plan for the three remaining phases. Our concept of the overall project also will be summarized, first to provide a perspective for expectations and results, and second, to define the planned magnitude of effort. The project is deliberately designed so that each phase is (1) as self contained as practical and (2) results in a useful research product. A brief description of the planned research phases is as follows.

6.1 THE GENERAL PLAN

The objective of the feasibility studies, conducted in Phase One, was to evaluate the potential for obtaining useful data regarding ionosphere properties in the nighttime lower D-region using the mode conversion phenomenon to gather information. The investigation included (1) examination of research literature both ionosphere and meteorological to derive clues regarding important phenomena that might be observable, (2) further study of the experimental concept through assessment of the Omega validation phase measurement data, (3) exploration of the practicality of conducting measurements in the Western Pacific, (4) investigation of opportunities for cooperative efforts with other researchers, (5) preparation of a detailed project plan and budget, and (6) preparation of a paper. The paper being prepared describes phenomena considered worthy of investigation and the experimental concept, including clues of measurement possibilities derived from Omega validation measurements.

The objective of the experiment planning and design phase, Phase Two, will be to conduct all the necessary preparations for experiment implementation. This effort will include (1) selecting candidate site locations for signal recording, (2) exploring possibilities for cooperative efforts both in the U. S. and internationally, (3) determining logistics, (4) conducting a trade-off analysis of expected derivable information versus number and location of sites, (5) preparation of an experiment plan including trade-off options, and (6) preparation of a paper describing the experiment plan and expected research products.

The objective of the experiment implementation phase, Phase Three, is to fab-

ricate and install measurement systems in accordance with the selected plan. This effort will include (1) final selection and negotiation of measurement sites, (2) assembly/fabrication of measurement equipment, (3) equipment installation and training as required for cooperative efforts, (4) demonstration of measurement feasibility, i.e., derived proof of concept, and (5) preparation of a paper describing the installed experimental setup, including a detailed description of the measurement equipment and its demonstrated capabilities. The measurement installation will be a phased effort, and some preliminary measurements from the proof of concept effort will be included in the paper.

The objective of the experiment conduction, analysis and interpretation phase, Phase Four, will be to derive new information on the lower D-region ionosphere, particularly its dynamics and variability. Important avenues of exploration will include (1) determining the dominant characteristics, (2) determining both predictability and variability, (3) establishing diurnal and seasonal patterns, (4) relating phenomena to mid-latitude and other altitude regimes, and (5) achieving a better understanding of the contribution of this region to the total earth dynamics. The phenomena suitable for investigation will be of intermediate scale, several megameters on a side (see the discussion of measurement concepts for an explanation). Assuming experimental success, a series of scientific papers will be prepared, each focusing on a specific topic of inquiry.

The planned technical effort will be presented by project phases. The project phases overlap in time. The relation of technical activity and accomplishments to the phases and calender time will be described in the discussion of schedules.

6.2 A PLAN FOR PHASES TWO THROUGH FOUR

The Phase One effort built a foundation for the follow-on research. The major activity was to develop the measurement concept and its associated value for ionosphere research. The knowledge and insights gleaned has become the basis for this follow-on plan.

6.2.1 PHASE TWO: EXPERIMENT PLANNING AND DESIGN

During this phase the broad concepts established in Phase One will be converted to detailed plans and preparations for experiment implementation. A detailed specification for phase and amplitude measurements will be prepared, including specifications of major components of the measurement equipment and cost estimates. The candidate sites selected on the basis of theoretical considerations will be examined for feasibility of implementation. This examination will include practical, logistic, and cooperative considerations and will involve dialog with technical and administrative personnel in the countries having jurisdiction over the candidate locations. Recording sites will be selected and methods for equipment installation and operation determined. An implementation and measurement plan will be prepared that includes operation details, installation procedures and schedules, logistics and maintenance procedures, and technical coordination. The level of detail will be determined by assessing the coordination needs for maintaining field operations. An important overall objective of this research is to relate the findings of the planned experiments to other research products. Thus a continuing effort will be made to establish cooperative efforts both in the U. S. and internationally. We expect that establishing cooperative efforts will strongly influence details of the experiment design and the procedures for follow-on data interpretation. Software adaptation of VLF ionosphere reflection codes for the interactive computer workstation development effort will continue. The products of this phase will include a paper describing the experiment, plans for implementation, and expected research products.

6.2.2 PHASE THREE: EXPERIMENT IMPLEMENTATION

This phase, in accordance with the selected plan of Phase Two, includes fabrication, installation of measurement systems, and training as required for cooperative efforts. Since the first installation of equipment in the measurement region will occur during this phase, a demonstration of measurement feasibility (i.e. a proof of the experiment concept) will be made. The measurement installation will be a phased effort largely determined by budget resources. The phased installation will allow us to capitalize on the early experience before finalizing the overall experiment design. However, since the experiment is designed to study dynamic phenomena, we want to conduct a fully implemented

experiment for at least a year. One product of this phase will be a paper describing the installed experimental setup, including a detailed description of the measurement equipment and its demonstrated capabilities. Some preliminary measurements from the proof of concept effort will be included in the paper.

6.2.3 PHASE FOUR: EXPERIMENT CONDUCTION, ANALYSIS AND INTERPRETATION

Emphasis in this phase will be on deriving new information on the lower D-region ionosphere, particularly its dynamics and variability. The interactive computer workstation capability assembled in Phase Two will be used to explore theoretical modeling of VLF ionosphere interaction. Initially the analysis will be directed to developing and testing experiment and experiment interpretation concepts. This initial analysis will be largely scenario based. Later this workstation will be used to investigate interpretations of the measurements. The data collection effort is expected to be routine, although allowances will have to be made for failures and down time. Data processing and analysis will be a dynamic endeavor with new techniques and procedures being devised as knowledge and insights are gained. The above cited avenues of exploration will all be pursued with priorities dictated by data interpretation. As already evidenced from the Phase One effort, many new insights are being and will continue to be derived. We expect that the most rewarding findings will result from pursuing discoveries made during research.

6.3 SCHEDULE PLANNING

This plan for a four-year period, covers the remaining phases of the proposed project. The Phase Two effort of this continuing project will be primarily preparation for experiment implementation; the effort includes (1) detailed planning, site selection and negotiation, and measurement equipment design and (2) derivation of a workstation analysis capability. This later effort will be heavily oriented towards computer code adaptation and checkout. The Phase Three effort will include (1) equipment fabrication, installation and training, (2) experiment checkout measurements, and (3) preparation of the analysis tools. Phase

Four will consist of experiment operation, data reduction, and data analysis and interpretation.

Geophysical phenomena are known to be highly variable with season and to vary greatly from year to year for the same season. For this reason we consider it important for the measurement effort to span a two-year period. This consideration has strongly influenced our plans to include as much overlap as practical early in the project and to extend the project into a fourth year.

The schedule for the various tasks is presented in Table 2. The Phase Two effort is scheduled for an investigation period of eight months. The Phase Three effort is scheduled to partially overlap Phase Two in order to initiate measurements as soon as practical. The total period for Phase Three is scheduled for ten months. The schedule for both Phases Two and Three includes allowances for delays in establishing cooperative arrangements for implementing measurement sites. The Phase Four schedule includes a parallel effort for measurements and analysis. A period of three months is scheduled following the measurement operations for final interpretive analysis and report preparation. A final report is scheduled at forty months from the start date of Phase Two. A series of papers will be prepared for journal submittal that describe experiment activities and analysis results.

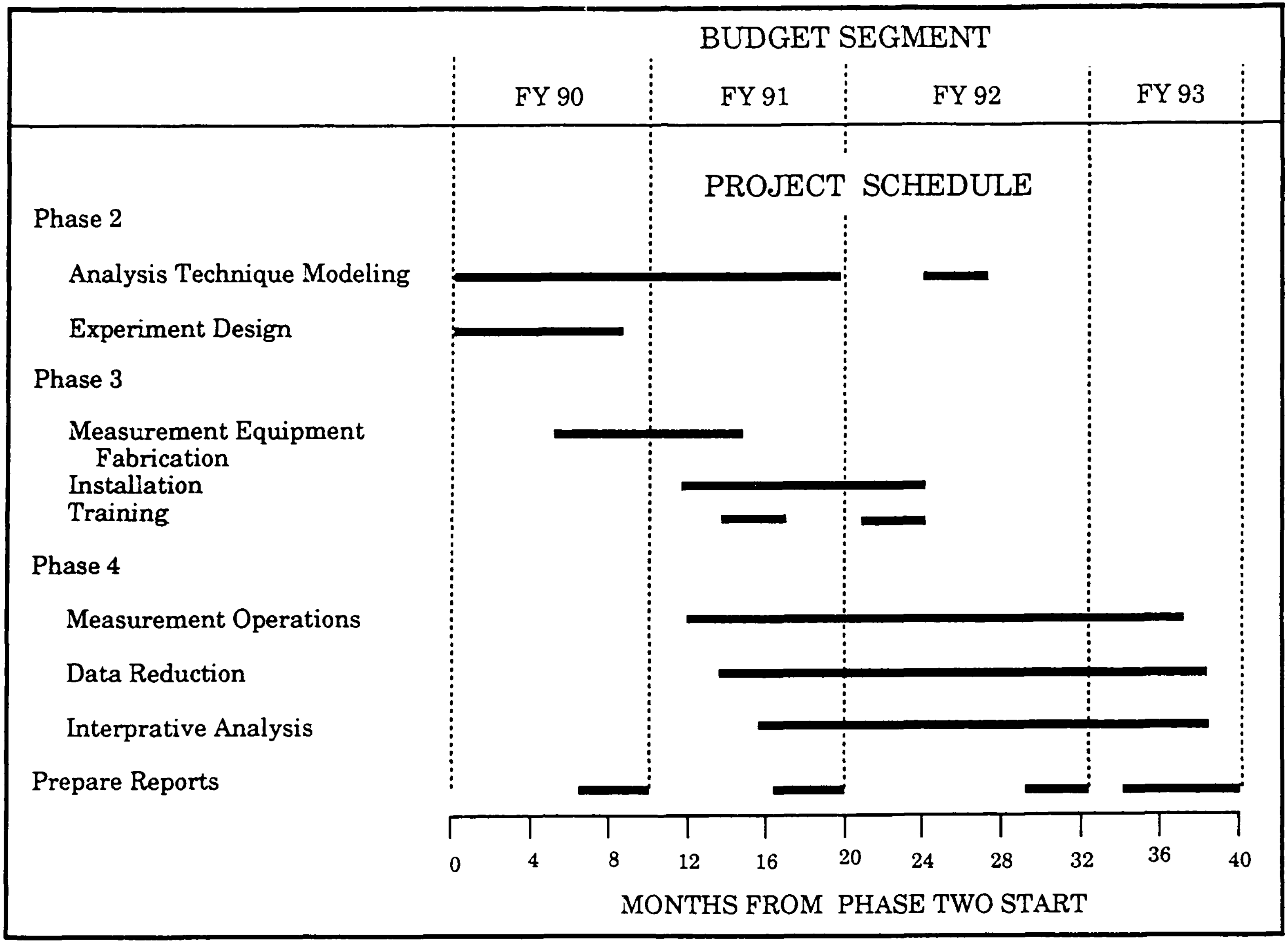

Table 2. Planned Research Schedule

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15 June 1990

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REF: Contract N00014-89-C-0134

Dear Mr. Joiner:

IWG Corp. is pleased to submit the enclosed Technical Report for Phase I of Contract N00014-89-C-0134 of 1 May 1989, entitled "D-Region Equatorial Ionosphere Research." Distribution of this Report is as per the Contract.

Sincerely,

Lawrence B. Gratt
Lawrence B. Gratt,
President

Enc.

cc. ACO, code S0514A (1 copy)
Director, NRL, Code 2627 (1 copy)
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Verne E. Hildebrand